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Aerial thermal infrared imaging and baseflow filtering analysis for river baseflow estimation in Lake Pyhäjärvi catchment, SW Finland

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Tiivistelmä/Referat – Abstract

The two input rivers of Säkylä's Lake Pyhäjärvi: Pyhäjoki and Yläneenjoki, were studied with aerial thermal infrared imaging (TIR) analysis and baseflow program, in order to estimate the baseflow in the two rivers. From the helicopter- assisted TIR survey made in July 2011, almost 200 groundwater discharge sites were located in the two studied rivers. The groundwater discharge anomalies were categorized in 5 different classes: 1) spring/springs, 2) cold channel connected to the main channel, 3) diffuse discharge to river, 4) wetland/ wide seepage, 5) unknown anomaly. In addition, a temperature analysis was performed from the studied rivers. In both rivers, pattern of increasing river water temperature from headwaters towards river outlet were discovered with temperature analysis.

The baseflow share estimate was made with baseflow filtering program which uses recursive digital filter for signal processing. Mean baseflow share estimation from four years: 2010-2013, were 70 % for River Pyhäjoki and 54 %, for River Yläneenjoki. Larger baseflow portion, lower river water temperature and wide diffuse discharge areas of River Pyhäjoki indicate that Pyhäjoki is more groundwater contributed than River Yläneenjoki. Previous studies made from the Lake Pyhäjärvi catchment have signs of higher groundwater share in River Pyhäjoki catchment, as well.

However, TIR and baseflow estimation results of this study have to be dealt with caution. TIR results represent momentary circumstances and GWD locations are interpretations. There are also many factors increasing the uncertainty of the temperature analysis and observations of GWD anomalies. The results of baseflow analysis has to be interpreted carefully too because baseflow filtering is pure signal processing. However, this study shows that River Pyhäjoki and River Yläneenjoki have groundwater contribution.

There is a difference in groundwater share in the two studied rivers. In River Pyhäjoki the larger groundwater share (70 %) is related to coarser grained glacial deposits in the river catchment. In TIR results, the influence of headwaters of the River Pyhäjoki, fed by two large springs: Myllylähde and Kankaanranta were emphasized. The two feeding springs are connected to the Säkylä-Virttaankangas esker complex. In River Yläneenjoki catchment, where GW portion was estimated to be smaller (54 %) and GW anomalies where mostly discrete, there are only two little till groundwater areas near the river channel and the catchment is characterized by finer sediments than River Pyhäjoki catchment.

Avainsanat – Nyckelord – Keywords
TIR, baseflow, Lake Pyhäjärvi, River Pyhäjoki, River Yläneenjoki, hydrogeology

Säilytyspaikka – Förvaringställe – Where deposited

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Tiivistelmä/Referat – Abstract

Säkylän Pyhäjärven kahden laskujoen, Pyhäjoen ja Yläneenjoen, pohjavirtaamaa arvioitiin infrapunakuvauksen (TIR) ja Baseflow- analyysin avulla. Heinäkuussa 2011 tehdyssä helikopteriavusteisessa TIR-kuvauksessa jokisysteemeissä ja niiden varsilla havaittiin yhteensä lähes 200 pohjaveden purkautumiskohtaa. Pohjaveden purkautumiseen liittyvät lämpötila-anomaliat jaettiin viiteen eri luokkaan, jotka olivat 1) lähde/ lähteiköt, 2) kylmä sivu-uoma, 3) diffuusi purkaus jokiuomaan, 4) kosteikko/ tihkupinta, 5) tunnistamaton anomalia. Tutkituista joista tehtiin myös lämpötila-analyysi, jossa havaittiin, että molemmissa jokisysteemeissä vesi lämpenee yläjuoksulta alajuoksulle.

Pohjavirtaamaan osuutta arvioitiin myös Baseflow- ohjelmiston avulla. Ohjelmisto erottaa joen virtaamasta pohjavirtaaman osuuden signaalin prosessointiin perustuvan silmukoivan filtteröinnin avulla. Vuosien 2010-2013 pohjavirtaaman keskimääräiseksi osuudeksi saatiin Baseflow-ohjelmistolla 70 % Pyhäjoelle ja 54 % Yläneenjoelle. Samankaltaisia tutkimustuloksia on esitetty myös aiemmin julkaistuissa Pyhäjoen ja Yläneenjoen pohjavesiosuuksia käsittelevissä tutkimuksissa. Suurempi pohjavirtaama, pienempi jokiveden lämpötila ja laaja-alaiset pohjaveden purkautumisanomaliat osoittavat, että pohjaveden osuus Pyhäjoessa on suurempi kuin Yläneenjoessa.

TIR- tutkimuksen tuloksia sekä pohjavirtaamalle laskettuja osuuksia on syytä tarkastella kriittisesti. TIR- aineistoista saadut tulokset kuvaavat vain hetkellisiä olosuhteita ja havaitut pohjaveden purkautumispaikat perustuvat kuva-aineiston tulkintaan. TIR- aineistosta tehtyyn lämpötila-analyysiin ja pohjaveden purkautumispaikkojen havainnointiin liittyy myös paljon epävarmuustekijöitä. Pohjavirtaama-analyysin tuloksia täytyy tulkita varoen, sillä pohjavirtaaman suodattaminen virtaama-aineistosta perustuu puhtaasti signaalien prosessointiin. Lämpökamera-aineiston tulokset ja pohjavirtaaman arvioinnista saadut tulokset osoittavat kuitenkin, että pohjaveden vaikutus on havaittavissa sekä Pyhäjoessa että Yläneenjoessa.

Pohjaveden vaikutus tutkituissa joissa on erilainen. Pohjaveden suurempi osuus (70 %) Pyhäjoessa liittyy Pyhäjoen valuma-alueen karkearakeisempaan maaperään. Infrapuna-aineiston perusteella pohjaveden osuutta Pyhäjoessa lisää erityisesti kaksi suurta yläjuoksun lähdettä: Myllylähde ja Kankaanranta, jotka liittyvät Säkylä-Virttaankankaan harjukompleksiin. Yläneenjoella, missä pohjaveden osuus oli arvioitu pienemmäksi (54 %) ja pohjaveden purkautumisanomaliat pistemmäisemmiksi, joen lähellä on vain kaksi pienempää moreenivaltaista pohjavesialuetta. Lisäksi Yläneenjoen maaperässä on enemmän hienorakeisempia sedimenttejä kuin Pyhäjoella.

Avainsanat – Nyckelord – Keywords
TIR, pohjavirtaama, Pyhäjärvi, Pyhäjoki, Yläneenjoki, hydrogeologia

Säilytyspaikka – Förvaringställe – Where deposited
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CONTENTS

1. INTRODUCTION

Groundwater and surface water are usually connected to each other and the connection between them is often ignored in the water management (Winter et al. 1998). The variable ways of groundwater (GW) — surface water (SW) interaction in the river plain system are also often acknowledged (Woessner 2000). Groundwater effects to the water quality of streams and lakes by nutrient loading and GW is also connected to the water balance of riparian vegetation (Hayashi and Rosenberry 2002). The groundwater discharge (GWD) alters the chemical composition and temperature of the SW (Hayashi and Rosenberry 2002). Many different hydrogeological survey methods are needed to use, in order to fully understand the interaction between groundwater and surface water (Korkka-Niemi et al. 2012).

Innovative GW-SW research methods are needed to extract more information about the complexity of the water systems. New methods for river base flow estimation and GW-SW interaction studies help to improve water management, adaptation to climate change and environmental protection**.** The climate change increases the need of understanding the complexity of GW-SW connections and groundwater influenced ecosystems (Klove et al. 2004). The predicted climate change with the atmospheric temperature rise of 1.5 °C or more (IPCC 2018), is a risk to groundwater level changes in groundwater tables and groundwater quality in Finland (Vienonen et al. 2012). The changes in GW quantity, GW levels, and GW quality effects directly to the surface water quantity and quality.

There are several chemical and physical methods for studying the groundwater- surface water interaction. Most used chemical methods are as follows: chemical and isotopical tracers, hydrogeochemical separation and mass balance studies (e.g. Karesvuori 2015, Rautio and Korkka-Niemi 2015, Rautio et al. 2015, Rautio 2015). In addition to, chemical methods, several physical methods for studying the GW contribution in the river water, such as: PART- (Wiebe 2012, Wiebe et al. 2015), and baseflow and recession analysis based on flow data (Arnold et al. 1995) has been used. In the field, it is possible to measure seepage flux and hydraulic head differences in order to study GWD (Rautio and Korkka-Niemi 2011). Thermal methods are useful tools to study groundwater discharge into the lakes and river systems (e.g. Torgersen et al. 2001, Dugdale et al. 2015, Rautio and

Korkka-Niemi 2011, Rautio 2017). Thermal infrared survey (TIR) is one of the thermal methods used successfully in cold environments due to the optimal temperature difference between GW and SW in summer time (e.g. Rautio and Korkka-Niemi 2011, Dugdale et al. 2015, Torgersen et al. 2001, Rautio 2017).

Lake Pyhäjärvi in SW Finland has been the study site of a pilot project aiming to test new environmental survey and monitoring methods by Finnish Environment institute (Lepistö et al.2010). Aerial infrared surveys were one of the new environmental survey methods tested in Lake Pyhjäjärvi catchment in early 2010's performed by University of Helsinki. The unpublished TIR data is used in this study in order to estimate the groundwater contribution in the two inflow rivers. This same infrared data from Lake Pyhäjärvi shore and rivers Pyhäjoki and Yläneenjoki has already been used for choosing some interesting samping locations for Karesvuori (2015) master thesis. TIR surveys give catchment scale information about GW-SW connections throughout the watershed by detecting surface temperatures of the river water (Torgersen et al. 2001).

The Lake Pyhäjärvi catchment has been the most studied area in Finland in terms of water balance, nutrient loading of the rivers and GW-SW interaction (Gonzales et al. 2015, Ekholm et al. 2000, Kirkkala et al. 2012, Bärlund et al. 2007, Ventelä et al. 2007, Ventelä et al. 2011, Karesvuori 2015, Rautio and Korkka-Niemi 2011, Rautio 2015, Wiebe et al. 2017, Wiebe 2012 etc). The restoration of Lake Pyhäjärvi started in 1990s, leaded by Lake Pyhäjärvi institute (Ventelä et al. 2007). The main focus of the lake restoration is, and has been, diminishing the nutrient loading to the surface waters of the catchment area, in order to prevent the eutrophication of the lake and its inflow rivers (Ventelä et al.2007). The GWD in to the input rivers might have a remarkable effect to the quantity of nitrate loading of the lake (Hayashi and Rosenberry 2002). Lake restoration is the main motivation to study and understand the water and nutrient budget of the Lake Pyhäjärvi, as well.

Previous studies performed in the Lake Pyhäjärvi catchment indicate that there are SW-GW interaction in the Lake Pyhäjärvi shore and in the two input rivers (Rautio and Korkka-Niemi 2011, Rautio et al. 2015). The previous studies also suggest that the River Pyhäjoki has a greater GW effect than the River Yläneenjoki (Rautio and Korkka-Niemi 2015, Wiebe 2012, Wiebe et al. 2015, Karesvuori 2015). The prior water chemistry studies (Rautio and Korkka-Niemi 2015) and water balance studies indicate somewhat similar relative propotion of GWD than the hydrographical separation made by Karesvuori (2015).

The aim of this study is to investigate the applicability of aerial thermal infrared imaging (TIR) and baseflow filtering for river baseflow estimation in Lake Pyhäjärvi catchment. The temperature difference between GW and SW is used for identifying groundwater discharge locations and detecting GW-SW interaction in the two surveyed river catchments. Baseflow analysis are made from stream flow records provided by Finnish Environment Institute. Time series analysis like baseflow analysis are needed to support the TIR studies because of the interpretative and momentary nature of the TIR- studies**.** Previous isotopic, geochemical, PART- separation and hydrographic separation results are also used in this study to evaluate, confirm and support the results (Rautio and Korkka-Niemi 2011, Rautio 2015, Karesvuori 2015, Wiebe 2012, Wiebe et al. 2015). TIR analysis from two studied river catchment is expected to verify and improve the baseflow estimations made for the river catchments.

2. STUDY SITE

The largest lake of SW Finland, Lake Pyhäjärvi, and the lakes' inflow Rivers Pyhäjoki and Yläneenjoki have remained an interest of research for several decades. Sustaining the recreational use and tourism at the lake, also preserving the living on fishery, have been the main reasons for the persistent restoring of the Lake Pyhäjärvi and its subcatchments (Ventelä et al. 2007, Kirkkala et al. 2012). Different kind of means are used for sustaining relatively low algal biomass levels (Ventelä et al. 2007). The restoration projects related to Lake Pyhäjärvi and altering the input rivers related to the lake projection have an impact on the river environment.

2.1. Catchments

Lake Pyhäjärvi catchment is situated in Southwestern Finland and the lake catchment size is 149 km^2 (HERTTA database 21.4.2019). Lake Pyhäjärvi is a mesotrophic lake and it has a surface area of 155 km^2– whole lake drainage basin area reaches the size of 616 km^2 (HERTTA database 21.4.2019, Ventelä et al. 2007). The mean depth of the lake Pyhäjärvi is 5.5 meters and maximum depth of the lake is 26 meters (Ventelä et al. 2007). The water volume of the lake is approximated to be 849 $*10^6$ m^3 (Ventelä et al. 2007). The only outflow river of the Lake Pyhäjärvi is River Eurajoki. Two inflow rivers of lake Pyhäjärvi catchment: river Pyhäjoki and river Yläneenjoki are in focus in this study. According to Wiebes' (2012) water balance studies the inflow of river Pyhäjoki is 148 mm and river Yläneenjoki 483 mm per unit lake area in a year, respectively.

River Yläneenjoki catchment area is significantly large: 234 km^2 (HERTTA database 9.1.2020) and the drainage area is 51 % of the whole Pyhäjärvi drainage area (Ventelä et al. 2007. River Pyhäjoki catchment reaches size of 78 km^2 (HERTTA database, 9.1.2020). The length of river Pyhäjoki is approximately 17 kilometers (HERTTA database, 9.1.2020). The length of the main stream of Yläneenjoki is about 38 kilometers and the river is ending to the Makkarakoski area (HERTTA database, 9.1.2020). The average flow raters of the two studied rivers are (1972-2013): 2.0 m^3s^{-1} river Yläneenjoki and 0.7 m^3s^{-1} River Pyhäjoki, respectively (HERTTA database, 9.3.2020). Small Hevonniitunoja catchment is also included as an example of ditch with GWD in the agricultural environment (Figure 1,14).

Lake Pyhäjärvi catchment area is situated in boreal climatic zone where winters are cold and humid whereas summers are relatively mild (https://www.ilmatieteenlaitos.fi/suomen-ilmastovyohykkeet, site visited 9.3.2020). The average precipitation according to Meteorological Institute's statistics from 1981-2010 according to Kokemäki weather station is 4.8 °C and the mean precipitation is 614 mm (Pirinen et al. 2012). The average evaporation according to Jokioinen's measurement station is 500 mm (years 2006-2010).

Generally the Lake Pyhäjärvi catchment is low-relief – plain environment (Figure 1). The landscape topography ranges in elevation from 40 m (the mouth of River Eurajoki) to 145 m above sea level in the River Pyhäjoki catchment where the Virttaankangas aquifer is situated (Figures 1,2,3).

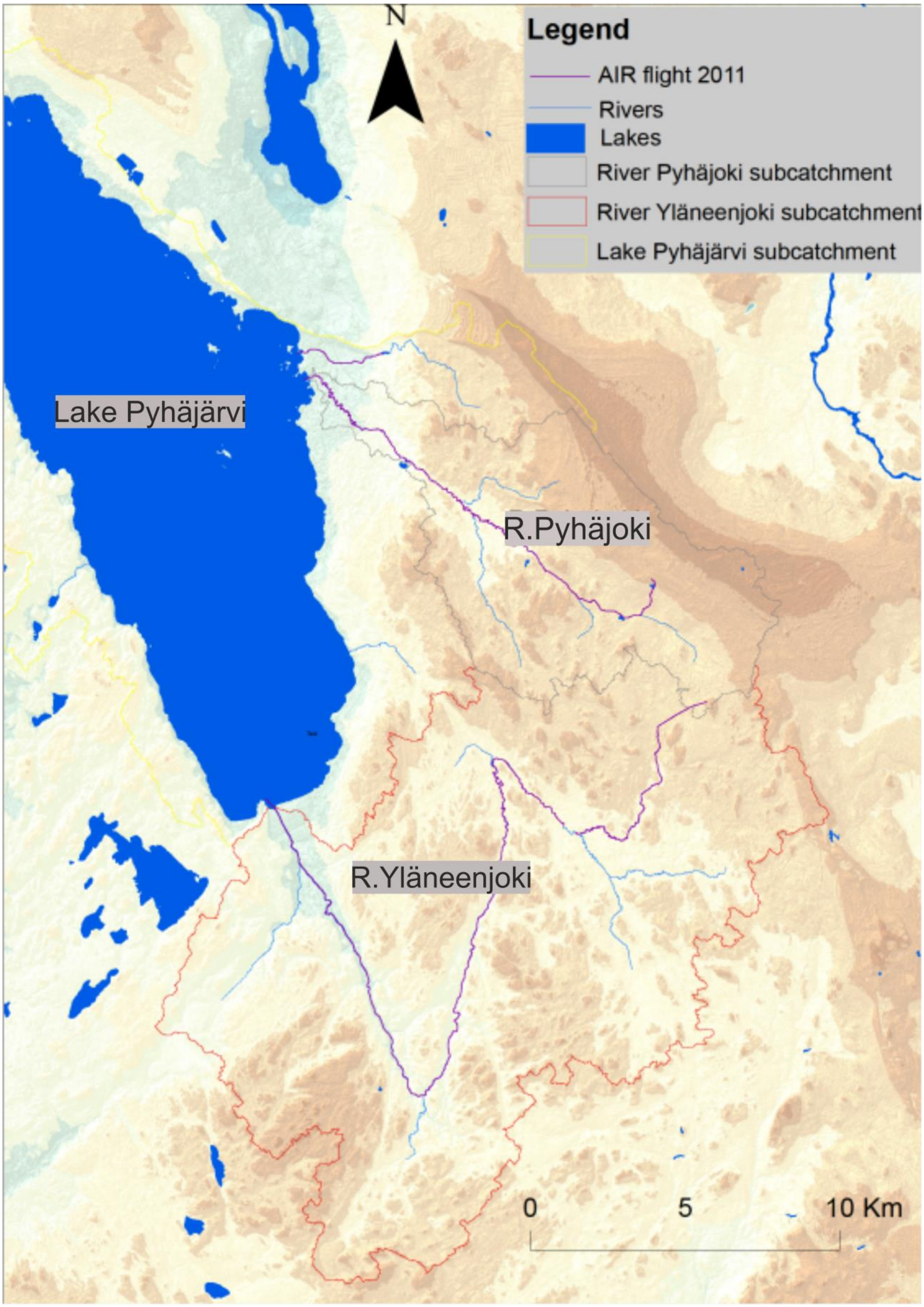

Figure 1. DEM of the study area and AIR flight of the two studied rivesr and Hevonniitunoja. DEM 2 x2 m © National land Survey of Finland, VALUE-tool, watershed, Uoma10 © Finnish Environment Institute.

2.2. Bedrock

The Lake Pyhäjärvi and the lake catchment itself is situated on mesoproterozoic silicate sandstone (Figure 2), which is a part of the Satakunta formation (Pokki et al. 2013). The three river mouths are also in the silicate sandstone bedrock area (Figure 2). The contact of rapakivi granite zone and the Satakunta sandstone in the West coast of Lake Pyhäjärvi, is a depression (graben) and it is the deepest spot of the Lake Pyhäjärvi (Eronen et al. 1982, Figure 2). Thick glacial deposits of the Säkylä-Virttaankangas esker are laying (70-100m in thickness) on the fractured bedrock zone (Maries et al. 2017, Artimo et al. 2003), this fracture zone might have a connection to northern part of Oripääkangas (HERTTA database 24.3.2018, Figure 5, Table 4). In addition, the Rivers Yläneenjoki and Pyhäjoki are both situating in valleys and they have been formed in depression zones (Kielosto et al. 2003a,b).

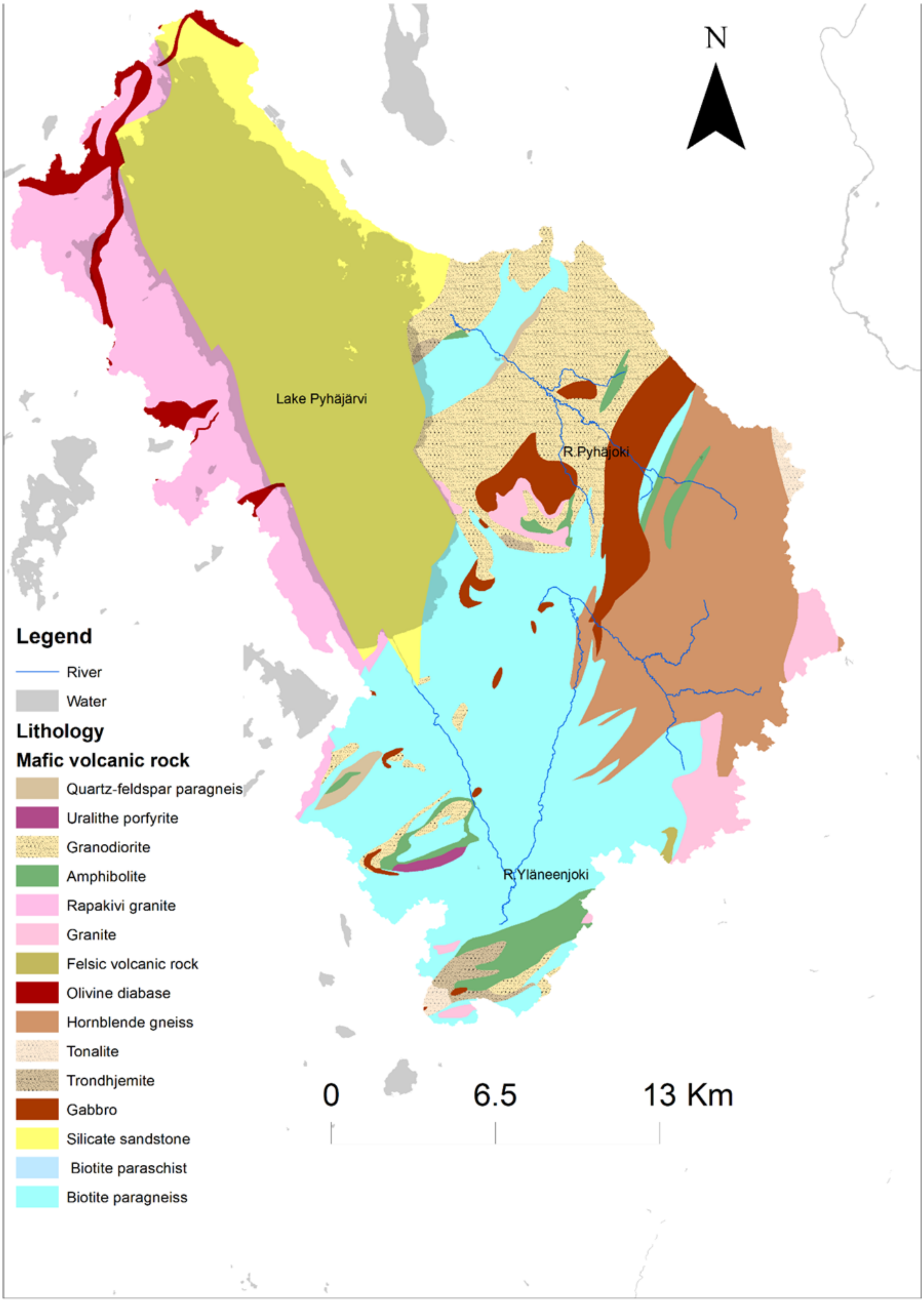

Figure 2. The bedrock of the study area and the two input rivers of the catchment. Altered from: Bedrock map: © Geological survey of Finland (1: 200 000) ©Watersheds,VALUE-tool, Uoma10. © Finnish Environment Institute.

There are granites in the south-west side of the River Pyhäjoki (Figure 2) and granite is also found on the edges of the River Pyhäjoki and Yläneenjoki subcatchments (Figure 2). Olivine diabase is cutting the rapakivi granite of Westside of the Lake Pyhäjärvi (Figure 2). The River Pyhäjoki catchment has a significant amount of gneiss and granodiorite (Figure 2). In both river catchments there are amphibolite in relatively small zones (Figure 2). River Yläneenjoki is mainly in biotite paragneiss /schist area and hornblend gneiss area (Figure 2). River Pyhäjoki has also a significant biotite paragneiss areas in the catchment (Figure 2).

2.3. Quaternary environment and surficial deposits

The lake Pyhäjärvi catchment have mainly Late Weichselian glacial deposits laying on the Precambrian bedrock (Johansson et al. 2011). These glacial deposits: gravel, sand, till and clay with Holocenes’ post-glacial clay, represent surficial deposits of the study area (Artimo 2002). Late Weichselian interlobate and end moraines are connected to Säkylä-Virttaankangas esker complex (Johansson et al. 2011). As a matter of fact, the Säkylä-Virttaankangas- Köyliönjärvi esker complex is connected all the way to the Salpausselkä 3 (SS-III) ice-marginal formation (Mäkinen 2003, Figure 3). The Säkylä-Virttaankangas-Köyliönjärvi esker complex has been formed between two Baltic Sea ice lobes and it has been thought to have interlobate origin (Johansson et al. 2011, Punkari1980).

The conception of interlobate provenance of Säkylänharju- Pori Esker relies on the stratigraphical features, morphology and large size of the esker formation (Mäkinen 2003). Säkylä-Virttaankangas interlobate esker complex (Figure 4) is extensive (200 kilometers in length), and the esker is characterized by up to 100-m-thick glacial sediments (Mäkinen 2003) and fan lobe channels (Maries et al.2017). Säkylä-Virttaankangas comprises of large-scale depositional units with a wide range of internal structures (Mäkinen 2003). The esker core constitutes sand and gravel with mainly rounded sandstone pebble cobbles (Mäkinen 2003, Maries et al. 2017).

In the surrounding area of Säkylä-Virttaankangas and the lake Pyhäjärvi catchment, there are different types of sand deposits that have variable origin: glaciofluvial sand deposits, shore deposits and eolian deposits (Perttunen et al. 1984, Kielosto et al. 2003a, b). Common characteristics of till formations in the lake Pyhäjärvi catchment area is that those have been washed during the last glaciation (Kielosto 2003a, b, Salonen 1986, Perttunen et al. 1984, Punkari 1980). Thin shore deposits containing silt and sand are common in the Pyhäjoki subcatchment (Kielosto et al. 2003a). Furthermore, some washed silt and sand originated from Säkylä-Virttaankangas can also be found in the Yläneenjoki subcatchment, as well (Perttunen et al. 1984).

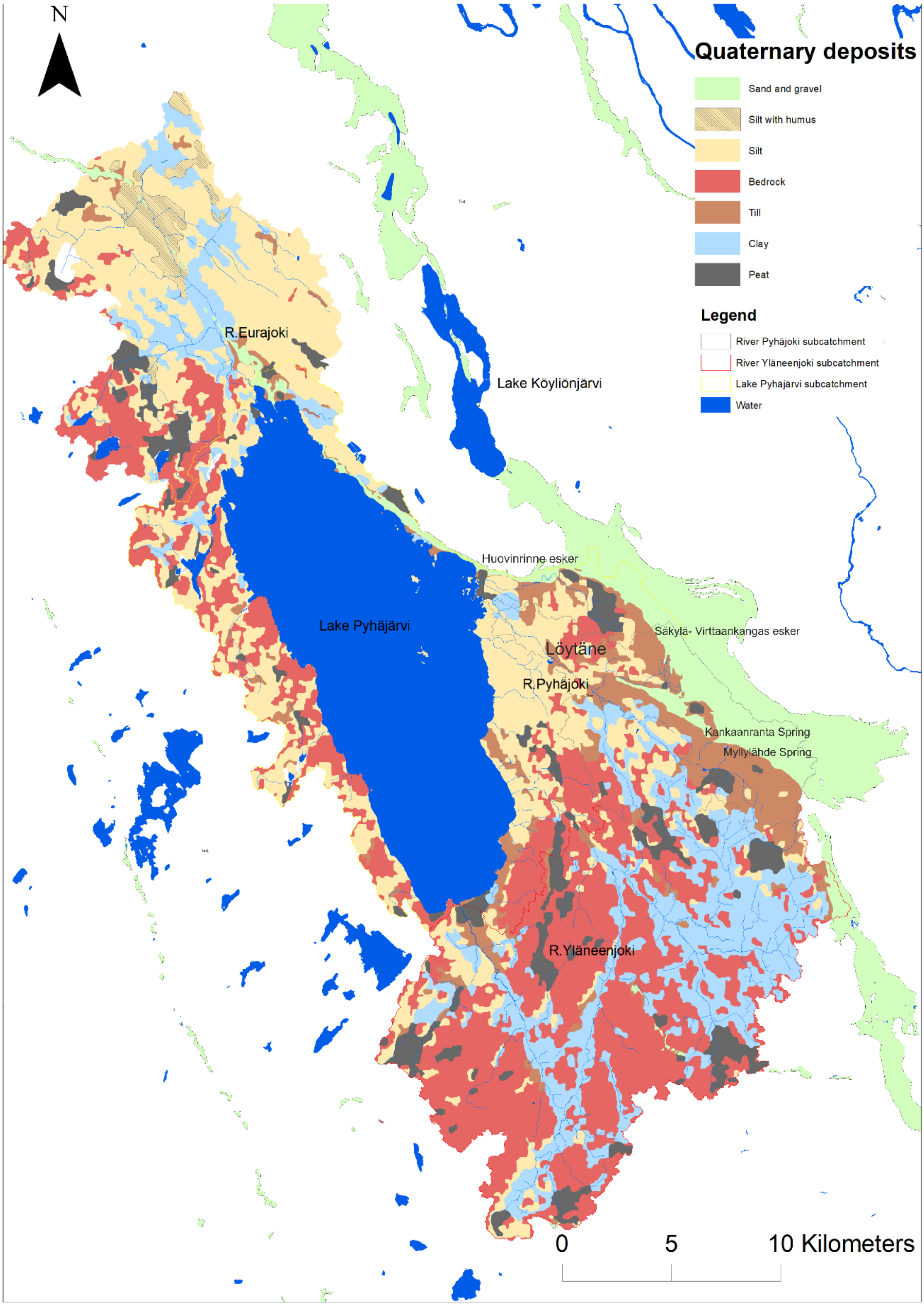

Figure 3. Quaternary deposits with sand and gravel reservs of the Säkylä-Virttaankangas esker complex. Watershed, Uoma10, VALUE © Finnish Environment Institute, Quaternary deposits, Aggregate sand and gravel © Hakku, Geological survey of Finland.

There are significant amount of bedrock outcrops or bedrock that has less than 1 meter thick deposits on top of it in the three studied subcatchments (Figure 3, Kielosto et al.

2003a,b). In the Lake Pyhäjärvi catchment, the glaciofluvial deposits of Huovinrinne esker characterize the northeast shore of the Lake Pyhäjärvi (Figures 3-4). In addition, there are significant amount of silt, till and peatland in the Pyhäjärvi catchment (Figure 3).

The main Quaternary deposits of River Yläneenjoki subcatchment area are clay, silt, peat and till (Figure 3). The clay is mostly in valleys and was deposited in the bedrock fracture zones (Figure 3, Perttunen et al. 1984). There are also some silt in the proximity of clay in River Yläneenjoki catchment (Figure 3). In River Yläneenjoki, the clay and other still water deposits in the fracture zones are mainly 10-20 meters thick and the maximum clay soil thickness studied in River Yläneenjoki map area is 26 meters (Perttunen et al. 1984). Clay deposits on top of tills are thinner, only 1-2 meters thin (Perttunen et al. 1984). In many cases, the clay deposits are covered with thin sand layer less than 1 meter (Perttunen et al. 1984).

There are sand and till deposits under fine grained soil deposits, but on the other hand, till deposited on the top of the sand and gravel is also common (Perttunen et al. 1984). In the stratigraphy of Yläne, it is common to have alternate layers of sand, silt and clay and some of the alternate deposits are clay-sand-clay deposits (Perttunen et al. 1984). Most of the peatlands in Yläneenjoki subcatchment are situating near of the River mouth (Figure 3).

The River Yläneenjoki subcatchment area is also characterized by different kind of till deposits (Perttunen et al. 1984, Koho et al. 1995). Thick till deposits (30-50 m) are common in the Yläneenjoki subcatchment area, according to the seismic refraction studies by Koho et al. (1995). The sediment in till deposits vary being mainly sandy till and clay-rich tills (Perttunen et al. 1984).

The River Pyhäjoki catchment consists mostly of silt, till, sand and gravel, peat and clay. The River Pyhäjoki catchment has approximate propotion of 10 % of peatland (Kielosto et al.2003a). Hummocky moraines with small amount of clay (0-2 %) and with significant share of sand, are common in River Pyhäjoki catchment and especially in Löytäne area (Kielosto et al. 2003a). In the East side of Pyhäjoki seismic refraction studies revealed that, the thickness of hummocky moraine varies from about 7to 15 meters (Kielosto et al.

2003a). The outwashed sandy moraine has higher hydraulic conductivity compared to the original sandy moraine (Kielosto et al. 2003 a, b)

2.4. Groundwater areas in the Lake Pyhäjärvi catchment

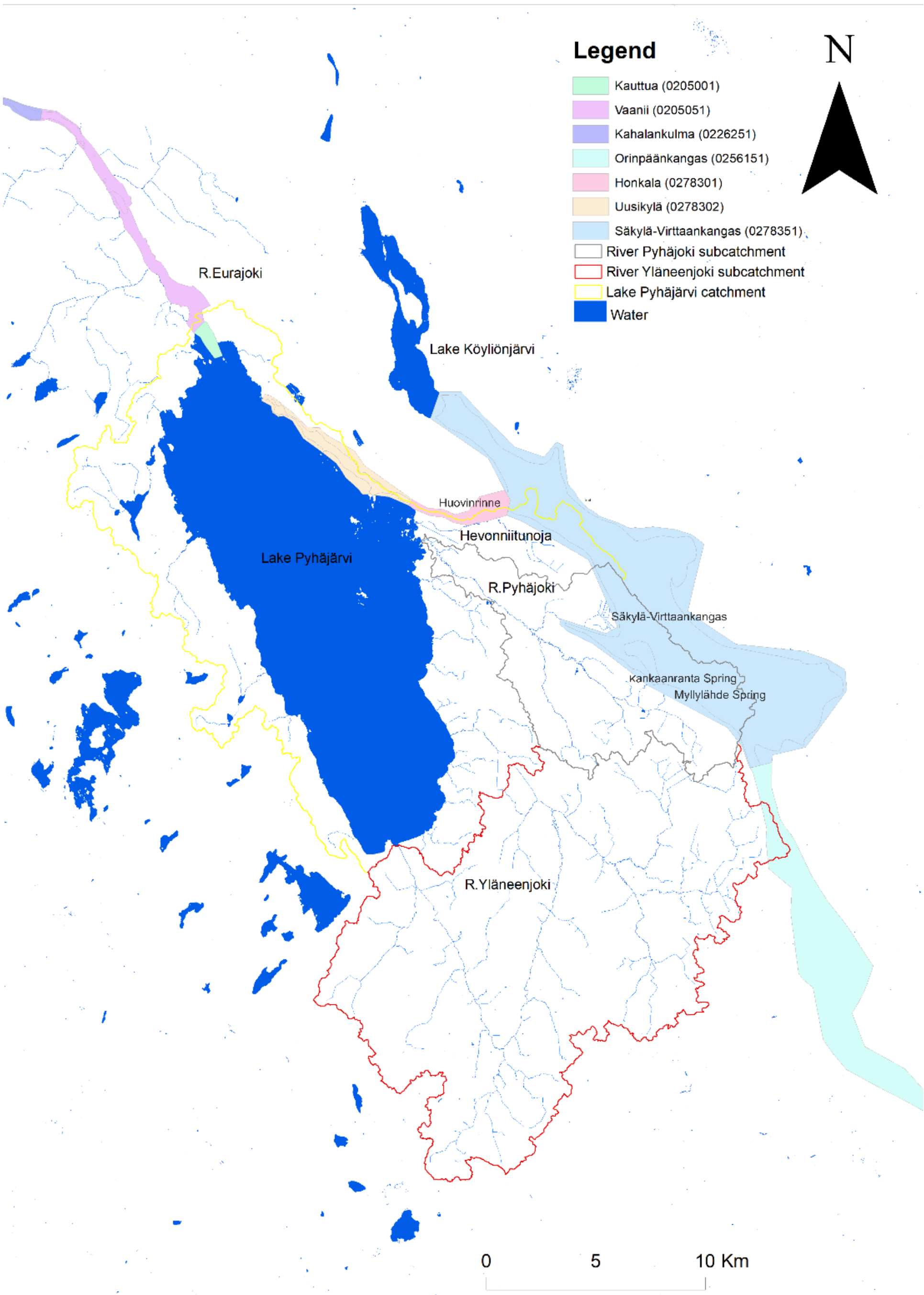

Figure 4. The main aquifers in the Lake Pyhäjärvi catchment. National Finnish Environment Institute: Watershed ©, Uoma10©, groundwater areas 2015 ©, VALUE-tool ©

Table 1. Most significant groundwater areas and groundwater recharge areas in the study site. National Finnish environment center ©

L.Pyhäjärvi SE shore and R.Pyhäjoki sucatchment	Classified GW area (km^2)	Recharge area (km^2)	Infiltration coefficient	Groundwater recharge estimate (average from m^3d^{-1})	Information about the aquifer/esker	Source flow (monitoring period 2010-2018 (m^3d^{-1})
Uusikylä (0278302)	5.74	2.25		1400		
Honkala (0278301)	3.1	1.84	0.45	1200	Contaminated (PCE, TCE) and GW pumping station closed	
Porsaanharju					side ridge related to Säkylä-Virttaankangas	Kankaanranta: 1305
Säkylä-Virttaankangas (0278351)	84.9	69.2	0.35	35000	interlobate/ marginal deposit and anticlinic	Myllylähde: 1983
R.Yläneenjoki subcatchment						
Oripäänkangas (0256151)	31.25	22.19	0.6	20000		

Kauttua aquifer is situated in the northern part of the Lake Pyhäjärvi (Figure 4) and the there is a managed aquifer recharge (MAR) facility called Lohiluoma. The contaminated Honkala aquifer (Table 1) is situated in the Huovinrinne esker which is partly under the lake and connected to Uusikylä esker (Artimo 2002, Rautio and Korkka-Niemi 2015). The tributary esker of Huovinrinne is connected to the Säkylänharju esker (Figure 4). The GW pumping station that extracted water from Honkala aquifer (Figure 4), has been closed in 1998 due to PCE, and TCE contamination from dry-cleaning laundry (Table 1, Artimo 2002).

Myllylähde spring is feeded by the Säkylä-Virttaankangas esker formation and spring Kankaanranta is feeded by tributary esker called Porsaanharju esker (Harjureitti.fi, visited 5.2.2020) that has been formed at the same time with the main esker. These two springs are feeding River Pyhäjoki: Kankaanranta feeds the river by 1300 $m^3d^{-1}$and Myllylähde spring almost 2000 m^3d^{-1} (Table 1). There are perched groundwater in the SE part of Säkylä-Virttaankangas and because the groundwater is near the surface there are artesian wells in the area (Kukkonen et al. 1993).

The large, 500-600 meter wide sand and gravel- esker core of Säkylä-Virttaankangas aquifer has high hydraulic conductivity, reaching the magnitude of 10^{-4} to 10^{-0}m^{-s} (Artimo et al. 2003). The classified aquifer of Säkylä-Virttanakangas reaches a size of 85 km^2 and has a recharge estimate of 35 000 m^3 d^{-1} (Table 1).

The main soil type is gravel and sand in the Oripääkangas groundwater area and the soil layers are relatively thick, 40 to 80 meters in the groundwater area (Hertta 23.3.2018, Figure 5). The groundwater discharges mainly to Spring Myllylähde of Oripää from Oripäänkangas groundwater area (HERTTA database 24.3.2018, Figure 5, Table 1). The Spring Myllylähde is one of the headwater source of River Yläneenjoki (Kukkonen et al. 1998, Figure 5). On the marginal zone of the Oripääkangas esker there are transition zones that consist of finer sediments like loam and clay (HERTTA database 23.3.2018). River Yläneenjoki catchment has also two smaller groundwater areas: Laihia and Uusikartano (Figure 5).

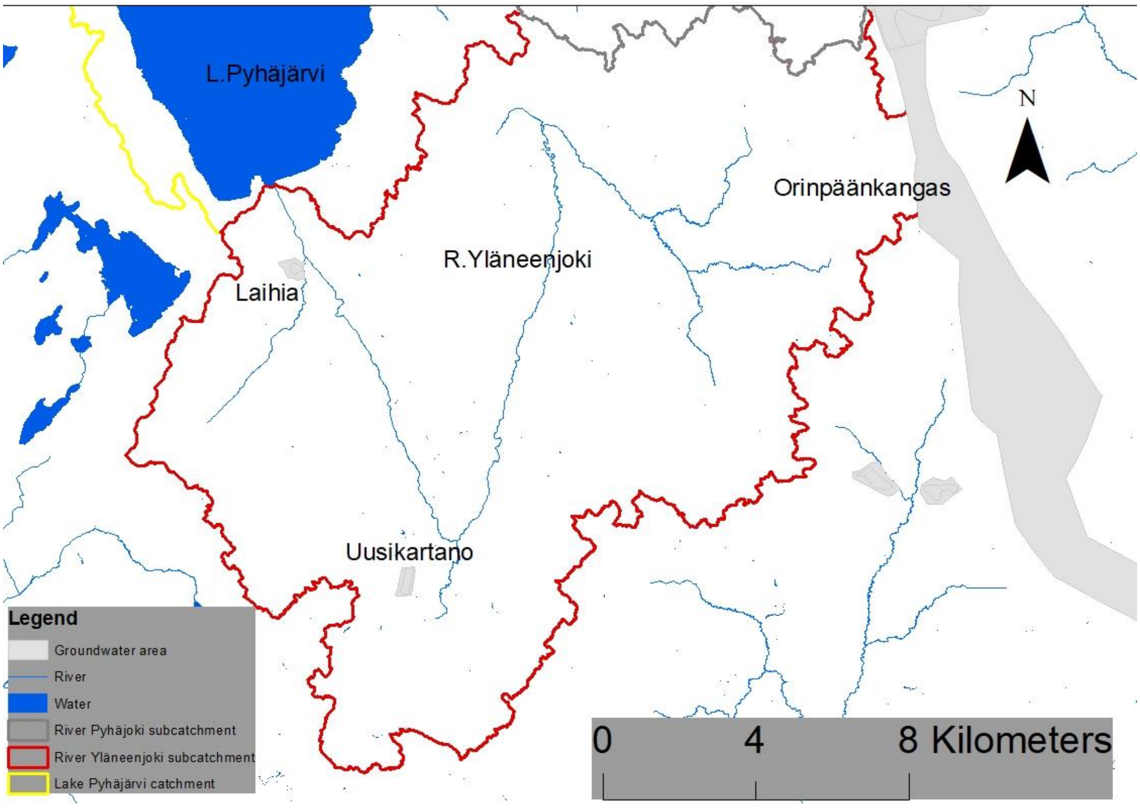

Figure 5. The groundwater areas in River Yläneenjoki catchment: Laihia, Uusikartano and little part of Orinpäänkangas. Groundwater areas 2015 , VALUE- tool , watershed and Uoma10 © National Finnish Environment Institute.

2.5 Land use

In River Pyhäjoki subcatchment the land is forest, shrubs and arable land (Figure 6, Table 2). In River Yläneenjoki subcatchment there are significantly more wetlands and less shrubs and herbaceous vegetation. Yläneenjoki subcatchment has almost an equal amount of urban land compared to River Pyhäjoki catchment. The forest industry dominates the subcatchment area when going further from the riparian area of the river. In the lake shore of southwestern Pyhäjärvi the land is mainly urban and also cultivated. A small amount of forest and shrubs are also located in the lake area. (Figure 6, Table 2).

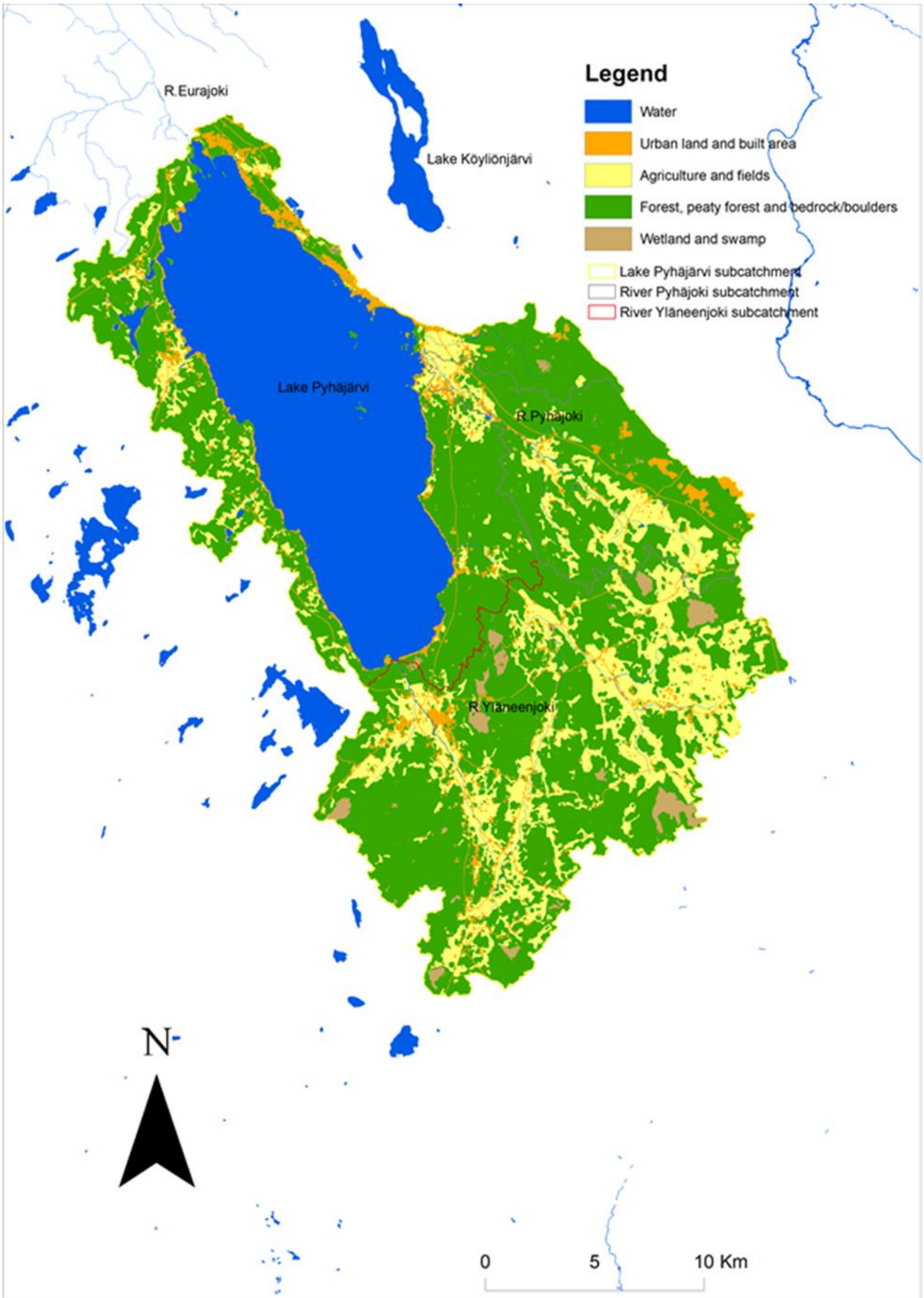

Figure 6. Land use in Lake Pyhäjärvi catchment. Corine land use cover 2012 ©watershed, VALUE-tool, Watershed and Uoma10 © Finnish Environment Institute.

Table 2. Land cover in Lake Pyhäjärvi catchment, River Pyhäjoki and River Yläneenjoki. VALUE- tool Finnish environment Institute © corine 2012 landcover

Corine landcover	Urban land	Agriculture and fields	Forest, peaty forest and pebble cobble	wetland and swamp	Inland water
R.Yläne	3.6	27.3	65.6	3.3	0.1
R.Pyhäjoki	5	23.2	55.8	15.4	0.4
Pyhäjärvi catchment	3.4	16.5	52.8	0.1	1.7

The Lake Pyhäjärvi is surrounded by cultivated land (Ventelä et al. 2007). Especially River Yläneenjoki has dense agriculture in the subcatchment and the river has a lot of nutrient loading from arable land (Kirkkala et al. 2012). Between years 2000-2005 River Yläneenjoki brought 53 % of the phosphorus (P) budget to lake Pyhäjärvi whereas the river Pyhäjoki brought only 12 % of P to the lake (Ventelä et al. 2007).

3. MATERIALS AND METHODS

3.1. Thermal infrared surveys

3.1.1. Field work

During the field campaign in July 2011 the weather condition was good : sky was clear and the air temperature was +22 °C (Figures – 7 A and 7- B). The temperature of surface water on the survey day was about +20° C and the groundwater +6 °C (Oral communication Anne Rautio 2017 and HERTTA database, Finnish Meteorological Institute). Mid-summer is the best time for TIR surveys because GW and SW temperature distinguish clearly from each other at that time (Korkka-Niemi et al. 2011).

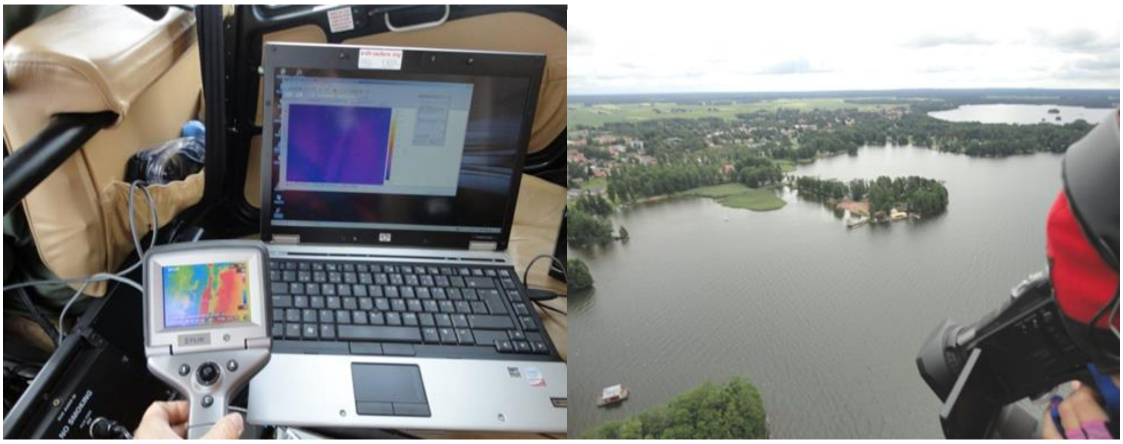

Figure 7. A-B. **A** The equipment used for TIR surveys and **B** view from the lake. © Kirsti Korkka-Niemi.

A FLIR ThermaCAM P60 TIR camera and an HDR-CX700 digital video camera were used together for data collection. The both cameras were held in a near vertical position on the side of the helicopter during the flight. The flight altitude ranged from 70–350 meters (above ground level) and ground resolution was between 0.15 and 0.5 meters. The spectral range of FLIR ThermaCAM was 7.5-13 µm and pixel resolution of the camera was 320x240. The FLIR system produced 5 to 6 frames of aerial infrared photos per second. The precision of FLIR system was informed by the manufacturer to be ±0.8 °C and the accuracy was ± 2.0 °C. or ± 2.0 %. The entire airborne flight covered also the shore of Lake Pyhäjärvi and outflow River Eurajoki and the amount of thermal images in this study were 50,000 in total. The images concerning this study are from the two inflow Rivers Pyhäjoki and Yläneenjoki and Hevonniitunoja ditch which included over 13, 000 TIR images.

This study focuses on the River Pyhäjoki and River Yläneenjoki (Figure 1). The airborne thermal imaging covered all the 22 kilometers of River Pyhäjoki and also the Kahilanoja feeding the river sourced by Myllylähde with length of 5 kilometers, (included in the 22 kilometers, Figure 1). Thermal imaging of the River Yläneenjoki covered almost 32 kilometers of the River Yläneenjoki (Figure 1). The main headwaters of River Yläneenjoki situated in the Makkarankoski area was not included in this TIR study (Figure 1.). The additional small subcatchment Hevonniitunoja was also included to this study to demonstrate the georefenced TIR images in the agriculture environment, (Figure 14). River Pyhäjoki was surveyed from the source to the river mouth and River Yläneenjoki vice versa from river mouth to the river source.

It took around 44 minutes to cover the study area with the TIR helicopter flight, Hevonniitunoja ditch and Myllyoja/ Kahilanoja feeded by Myllylähde included along the two input rivers: Yläneenjoki and Pyhäjoki. Some of the images could not be processed or interpreted because of blurriness caused by wobbling of the helicopter or the sight being out of the studied river channel. The filming disconnected in the River Yläneenjoki during 23 seconds and the length of the gap is about 660 meters of River Yläneenjoki and this part was left with no TIR data. Floating Vegetation and blurriness of the images also caused that some of the TIR images were left out of the processing and interpretation of categories.

3.1.2 Processing and tools for interpretations

The emissivity value of 0.96 was used in this study for TIR- processing. Information from Kokemäki weather station (around 20 kilometers from the tip of the lake), was used for the humidity and air temperature values for the TIR data processing. ThermaCAM Researcher pro 2.10 was used for preprocessing TIR-data and choosing the sites of aerial infrared images and mosaic images for illustrating the different kind of GWD categories. The flight altitude correction was performed with ArcGIS program by using LidarDEM 2x2m by extracting multivalues to points. Depending on the scale and importance of the exact temperature values, the GPS data of the helicopter flight can be replaced on the river to improve the accuracy of altitude correction. In this study the replacement would have improved the accuracy by 0.1-0.2 °C in some locations.

The interpretations of discharge categories and the temperature analysis of minimum radiant temperature were made from the photoflow of ThermaCAM Researcher pro 2.10 program. Each TIR-photo was analyzed one buy one. The minimum radiant temperatures were detected manually from each TIR-photo and the lowest temperature of each second was chosen. The identification of the minimum radiant temperature was made with the help of polygon tool to mark the limits of the studied river channel. Similar techniques have been used in previous studies when studying temperature characteristics of rivers in Finland (e.g. Rautio et al. 2015, Korkka-Niemi et al. 2011).

The limit for the temperature anomaly is decided to be at least 1.5-2 °C compared to the ambient river water temperature or surroundings of the anomaly. Most of the times, the setting of 0 or 1 is used for reflected temperature value. Too high reflected T value was used in this study for temperature analysis and it effects to the temperatures by decreasing the minimum radiant temperature approximately 0.7-0.8 degrees compared using values of 0 or 1. Different kind of radiations effecting to TIR surveys are represented in the (Figure 8).

The ideal season and timing of thermal imaging depends on the meteorological and seasonal conditions of the study area (Davis 2007). Data used in this study is collected in summer time when there is the maximum contrast between stream water and groundwater temperatures in Finland (Rautio et al. 2015, Davis 2007). In Finland, winter mapping with TIR- surveys could be used for prestudy of discharge locations and focusing the field study in order to save expenses (Rautio 2015). The diffuse and discrete GW anomalies in the river channel and riparian area are studied previously in Finland in summertime by Korkka-Niemi et al. (2011). The different kind of groundwater anomalies are interpreted from the ambient surface water and its surroundings by temperature differences. Only the surface layer (<0.1 mm) of the studied waterbody can be detected with airborne infrared surveys (Torgersen et al. 2001). The GWD locations were verified with the help of ortho video taken simultaneously with TIR and checking the tricky anomalies with Mapsite service of National land survey of Finland in order to reduce false interpretations.

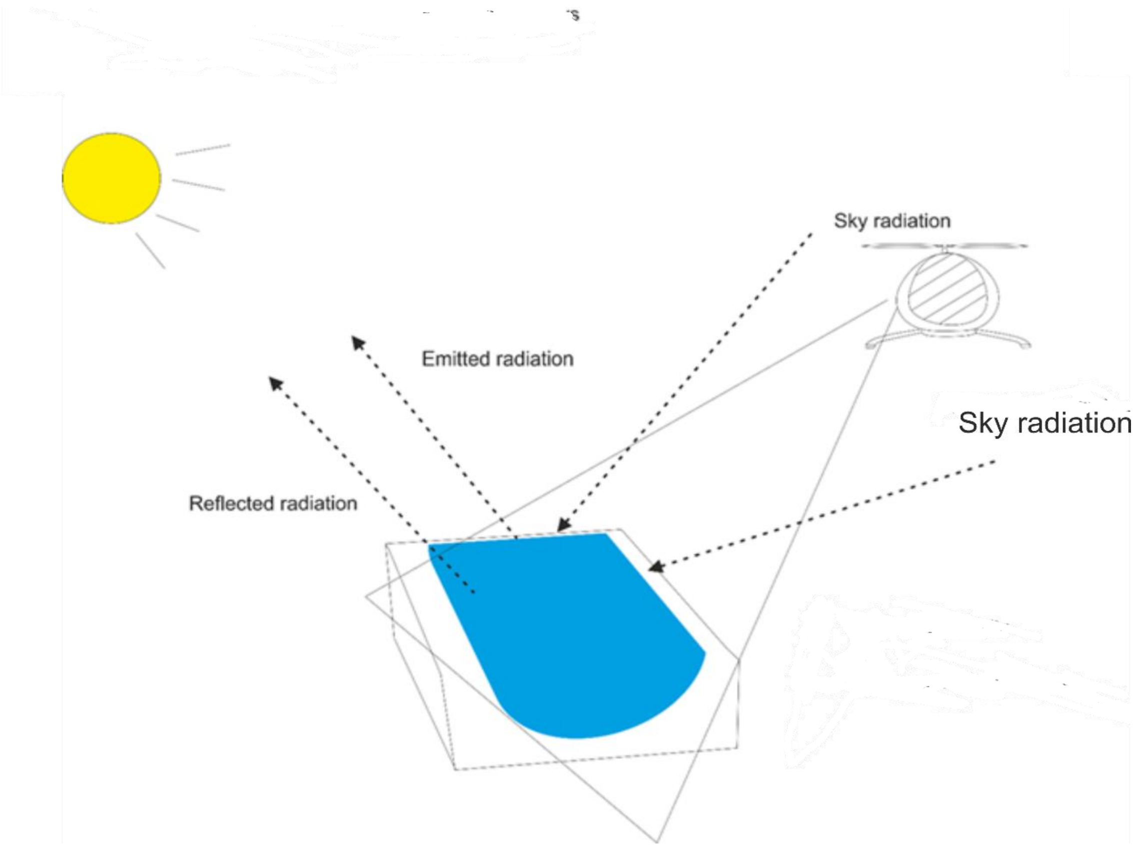

Figure 8. Different factors of radiation that affects to the TIR surveys in river environments. Altered from Torgersen et al. 2001.

The temperature values in this study are not compared with the river water reference temperatures measured the field trip, because the data of these temperatures measured in 2011 could not be found, any more. However, this study focuses on the relative temperature differences along the river catchments rather than actual temperature values.

3.2 Baseflow analysis

Finnish Environment Institute (Suomen Ympäristökeskus) and their open database were used for material of the flow rate data for baseflow analysis. The flow rate data was from flow monitoring stations of the two studied rivers located relatively close to the river mouths (Figure 9). The daily flow rates available in HERTTA database are mean values of the day and the flow rates are calculated with discharge curves based on the river water (RW) level measurements. (Figure 9, personal communication with Jarkko Koskela, Hydrolologist of Finnish Environment Institute, 20.11.2017).

Figure 9. The flow monitoring station in River Pyhäjoki, November 2019. Photo © Kirsti Korkka-Niemi.

The precipitation values were provided by Meteorological institute of Finland. The weather stations in the subcatchment areas and the average precipitations of the study period were as follows: Oripää, Teinikivi 2010-2013 642 (mm), Huittinen Sallila 636 (mm), Pöytyä, Yläne 609 (mm) (HERTTA database 15.3.2019).

3.2.1. Baseflow filtering

Baseflow is generally derived from available streamflow records using hydrograph separation techniques (Arnold et al. 1995). A recursive digital filter method for baseflow separation is used in this study (Arnold et al. 1995, Arnold and Allen, 1999). In this particular bflow.exe program the stream flow is divided into base flow and surface flow with digital filter called Lyne and Hollick filter (Arnold et al.1995, Arnold and Allen 1999, Figure 10). Automated separation technique provides a solution for defining the base flow directly from stream flow records (Arnold et al. 1995).

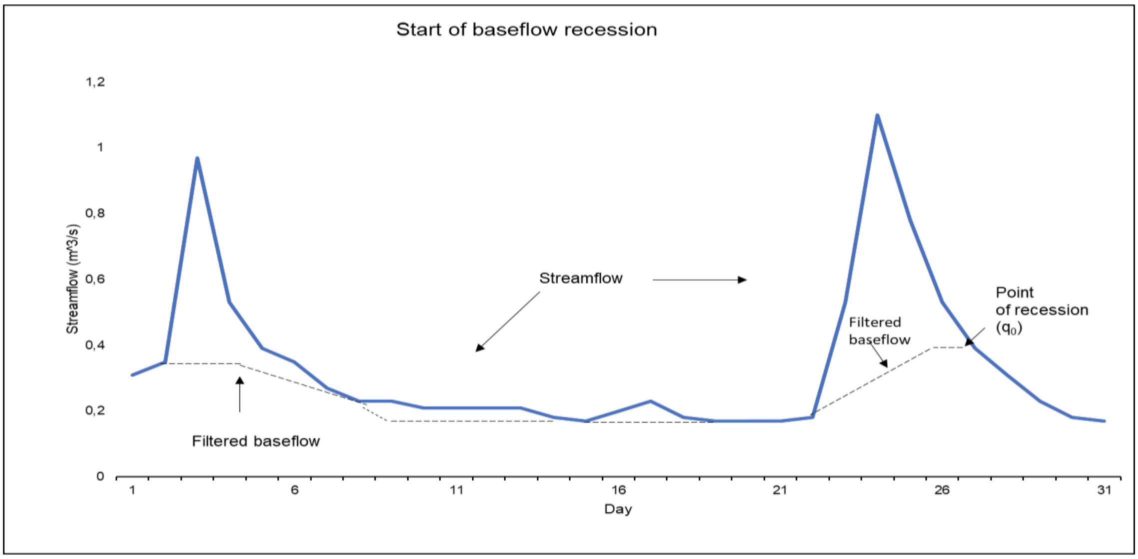

Figure 10. Simplified graph illustrating baseflow separation made by recrusive digital filter method (altered from Arnold et al. 1995, streamflow record from HERTTA database, River Pyhäjoki).

The daily streamflow data is generally passed three times through the recursive digital filter (Ladson et al. 2013, Nathan and McMahon 1990). The first pass is forward, second pass is backward and third pass is again forward, every time when the daily streamflow data is passed through the filter, the amount of baseflow is reduced (Arnold et al. 1995). The second pass reduces approximately 17 % and the third pass reduces approximately 10 % of the last baseflow estimation (Arnold et al. 1995). The filter value alpha= 0.925 is commonly used (Ladson et al. 2013) and is considered to be reasonable enough for baseflow estimation, even though using different filter values is a better option and gives more accurate baseflow results (Nathan and McMahon 1990).
Lyne and Hollick filter from (1979),

α=0.925 is calculated from equation:

$$q(f)\,(i) = (\alpha q_f(i-1) + (1+\alpha)/2(q_{(i)}-q_{(i-1)})\ \text{for}\ q_{f(i)}>0$$
otherwise
$$q_{(b)}(b) = q(i)-q_f(i) \qquad (1)$$

Arnold emphasises (1995) that automated baseflow separation software needs minimum of one months' streamflow data but it is preferred to use data from longer period in baseflow studies. The daily flow data has to be in the form of YYYYMMDD and after that the flow value has to be separated with at least one space. The streamflow data can be red from txt- file format by using DOS prompt window with bflow.exe program (Baseflow program manual, University of Calgary).

The estimation of baseflow is usually somewhere between the first and second pass if the precipitation infiltrates to the aquifer or aquifers in the catchment (Baseflow program manual, University of Calgary).

4. RESULTS

4.1 TIR results

The amount of interpreted thermal images in this study were over 13,200 in total and the images studied were only from two inflow Rivers Pyhäjoki and Yläneenjoki and small catchment of Pyhäjärvi where Hevonniitunoja ditch is located. 22 kilometers of River Pyhäjoki were studied: all the way from Myllylähde source to the outflow of the Lake Pyhäjärvi. Almost 32 kilometers of the River Yläneenjoki were covered from the Lake Pyhäjärvi to Myllylähde source of Oripää. The minimum radiant temperature were analyzed for each second of the TIR flight in the river systems. Whereas, about 200 GWD (Table 2) anomalies in the river waters and riparian areas of the two studied rivers were observed from the TIR flights.

4.1.1 GW Discharge categories

The classification were chosen to have five different kind of categories: spring or springs, cold channel connected to the river system, diffuse discharge to the river, wetland/wide seepage in the riparian area and unknown discharge category. The classification was defined as follows:

1 spring/ springs: spring or several springs discharging to the river system or in the riparian area or river bank (Figures 13B, 11A).

2 ditch/ creek/ springbrook: cold channel connecting to the river channel (Figure- 13A)

3 Diffuse discharge: diffuse discharge in to the river water, the category includes shoreline diffuse and wide diffuse discharge to the river water (Figure- 13D)

4 wetland/wide seepage: wetland or wide seepage in the riparian area (Figure- 13C)

5 unknown discharge class: the groundwater is discharging under riparian vegetation, or the category can't otherwise be verified from TIR data

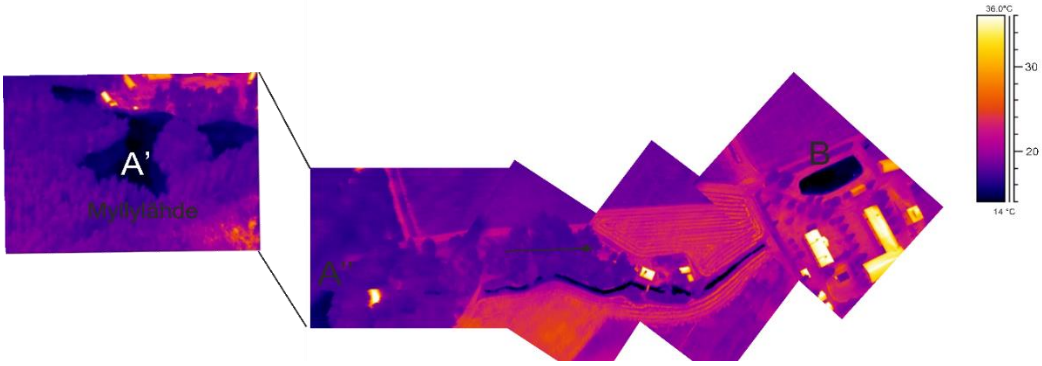

Figure 11.A', A', A''and B. Example of sourcing from Spring Myllylähde marked as A' and A'' with pond (B) with GW discharge seen from the bird perspective.

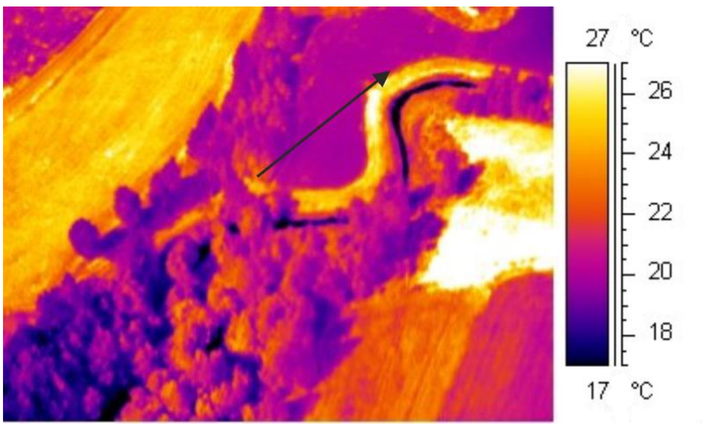

Figure 12. The river characteristics can be well seen from TIR surveys. Meandering River Pyhäjoki. The cold river water distinguish from the surroundings.

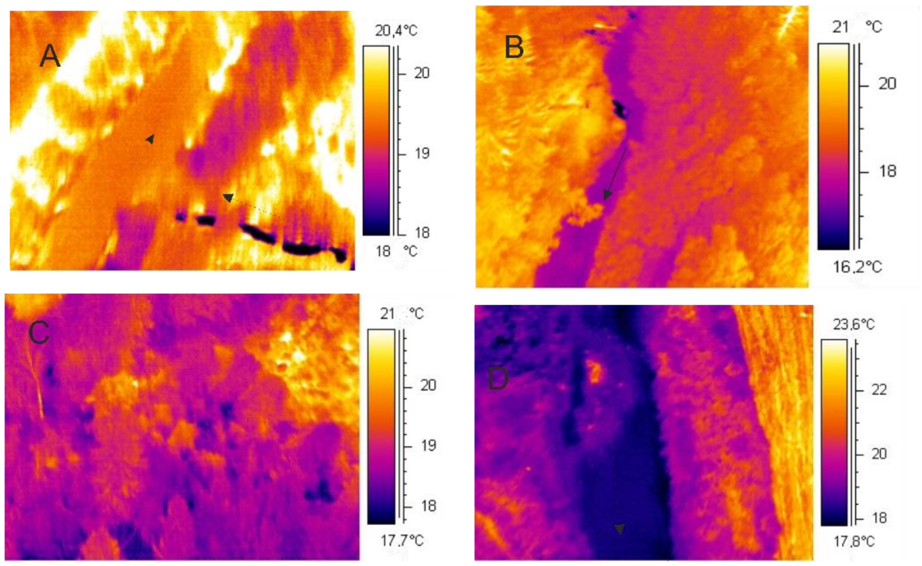

Figure 13. A-D examples of the four GWD categories in Rivers Pyhäjoki and Yläneenjoki.**A** Cold creek or tributary connected to the River Yläneenjoki. Springs discharging to the River Yläneenjoki, several small springs in the same TIR image. **B** Spring/springs discharging to the river. Some of the cold water temperature anomalies can be a cause to the rapid or rocks that emit and reflect lower temperatures compared to the surrounding. Scale. **C** wetland under vegetation and **D** Shoreline diffuse on the right side of the channel and wetland on the left upper corner in the image in River Yläneenjoki. Reflected temperature value of 0 was used in these example TIR images.

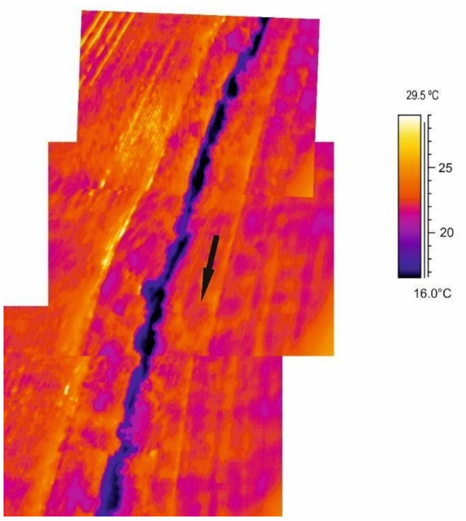

Figure 14. Hevonniitunoja ditch, with significant GWD. An example of mosaic TIR image from the lake Pyhäjärvi catchment. Reflected temperature value of 0 was used in the example TIR mosaic.

Table 3. GWD categories in the two studied Rivers Pyhäjoki and Yläneenjoki and their riparian area.

River	category 1	category 2	category 3	category 4	category 5	Total
	Spring/springs	ditch/creek	Diffuse discharge	wetland/wide seepage	unknown anomaly	
Pyhäjoki	5	3	10	0	1	19
Yläneenjoki	84	30	40	18	8	180

The River Pyhäjoki had only 19 GWD locations in total and River Yläneenjoki had 180 discharge locations detected (Table 2). Problem in this classification is that the wideness of the classified GWD location varies. The River Yläneenjoki had over 100 discrete anomalies that include springs and channels connected to the river (Table 3). Whereas River Pyhäjoki only had 8 locations where discrete anomalies were observed (Table 3). On the other hand, the anomalies were smaller in River Yläneenjoki and some diffuse classes were several kilometers long in Pyhäjoki. In this study the smaller springs in the same TIR image are marked in the map as one location to describe the area of GWD condition (Figure- 13B).

There are in River Yläneenjoki GW fed wetlands or wide seepage areas in the riparian zone. In addition, River Yläneenjoki had 40 wetland/ wide seepage areas (Table 3). Even the River Yläneenjoki had more diffuse discharge locations (40) to the river channel than River Pyhäjoki (8). the River Pyhäjoki was characterized by diffuse discharge to the river channel: either large diffuse area or diffuse clearly by shoreline (Table 3).

The unknown anomalies were either cold ditches or other mall channels or springs under the vegetation. Because of the vegetation coverage, there were no possibility to identify some of the anomalies. The River Pyhäjoki had only 1 and River Yläneenjoki had 8 anomalies with no specific class (Table 3).

There is a clear difference between the amount of discrete categories in these two rivers. The GWD locations of the two studied rivers are found in the Figure (15). Several categories are often found in same place close to each other (Figure 15). Categories and their possible connections to geological environment and land use is discussed more further in this study.

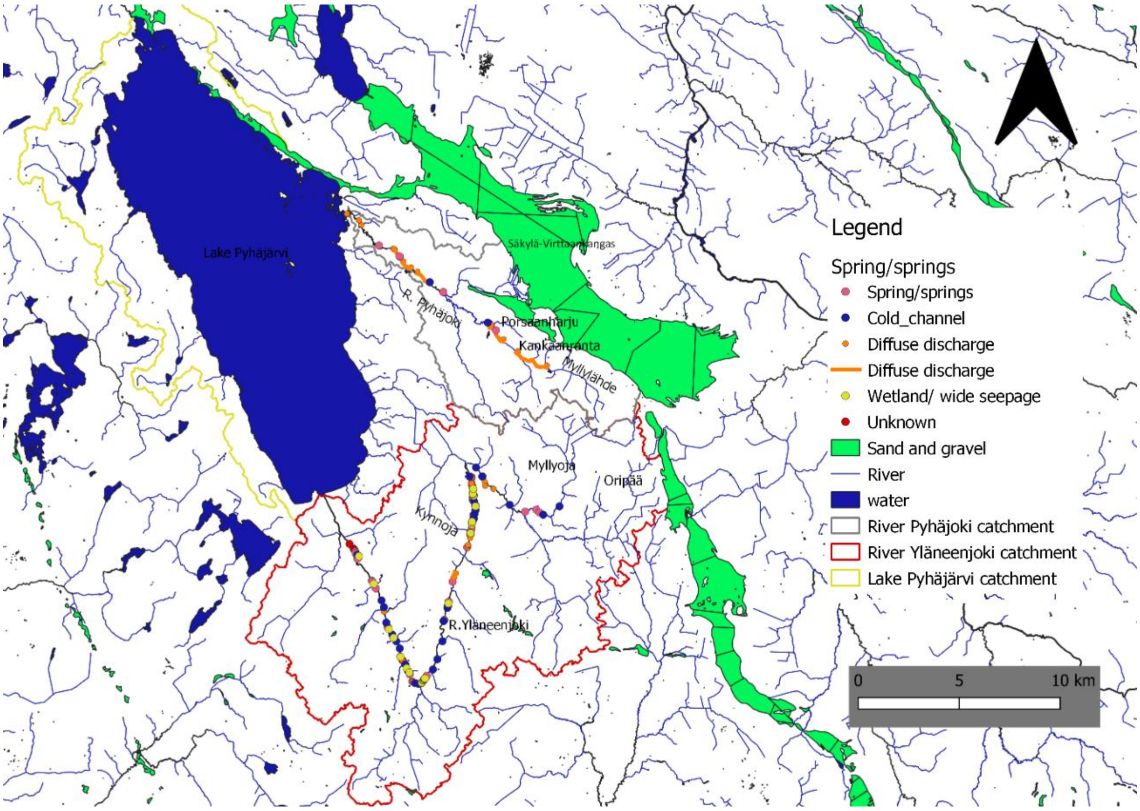

Figure 15. The discharge categories in the two studied river catchments. VALUE-tool Watershed, Uoma10 © Finnish Environment Institute, Sand and gravel, © Geological survey of Finland.

4.2 Baseflow Analysis

The main principal of the baseflow analysis is separating the groundwater contributed flow from the total discharge by using signal processing (Nathan and McMahon 1990). The digital filter carries out three passes with the filter equation (1) represented previously in this study (Nathan McMahon 1990, Arnold et al. 1995). The digital filter separates the high frequencies from the low frequencies (Nathan and McMahon 1990, Arnold et al. 1995), and the quick response of surface run off (high frequencies)- this makes the filter distinguish surface flow from the baseflow (Arnold et al. 1995). The discharge values from years 2010-2013 obtained from HERTTA database (5.4.2019) of Finnish Environment Institute were used for baseflow separation from surface runoff in this study.

4.2.1. Baseflow filtering

In the baseflow program, the minimum number of days (NDMIN) for groundwater recession alpha calculation were set as 5 days and maximum number of days (NDMAX) were set as 30 days. The default values for NDMIN was 10 and for NDMAX was 300 in the program.

Table 4. Mean discharge (Q), mean baseflow (Q) and baseflow fraction values of total flow for each pass of the two studied rives for years 2010-2013.The underlined results are from the year as airborne TIR surveys. HERTTA database.

	Q (mean)	**Bflow pass 1**		**Bflow pass 2**		**Bflow pass 3**	
R.Pyhäjoki	(m^3s^{-1})	(m^3s^{-1})	(%)	(m^3s^{-1})	(%)	(m^3s^{-1})	(%)
2010	0.53	0.36	69	0.28	54	0.23	45
<u>2011</u>	<u>0.8</u>	<u>0.56</u>	<u>70</u>	<u>0.47</u>	<u>58</u>	<u>0.38</u>	<u>47</u>
2012	0.88	0.64	73	0.51	58	0.44	50
2013	0.62	0.43	69	0.34	55	0.28	45
Variation	0.53-0.88	0.36-0.64	69-73	0.28-0.51	54-58	0.23-0.44	45-50
Mean	0.71	0.5	70.3	0.4	56.3	0.3325	46.8
R.Yläneenjoki							
2010	1.52	0.82	54	0.52	34	0.37	25
<u>2011</u>	<u>1.5</u>	<u>0.79</u>	<u>53</u>	<u>0.47</u>	<u>31</u>	<u>0.29</u>	<u>19</u>
2012	1.89	1.05	56	0.68	36	0.54	29
2013	1.5	0.83	54	0.54	35	0.36	23
Variation	1.50-1.89	0.79-1.05	53-56	0.47-0.68	31-36	0.29-0.54	19-25
Mean	1.61	0.8725	54.3	0.5525	34	0.39	24

The mean discharge (Q) of studied years varied in River Pyhäjoki from 0.53 to 0.88 m^3s^{-1} (Table 4, Figure 16) - and in River Yläneenjoki from 1.50 m^3s^{-1} to 1.89 m^3s^{-1} (Table 4, Figure 17). Roughly, the yearly mean discharge is three time larger in River Yläneenjoki than in River Pyhäjoki according to HERTTA database. The year 2010 had the lowest mean flow rate in both studied rivers (Table 4). The highest mean flow rates of the study period were in the year 2012: 0.88 m^3s^{-1} for the River Pyhäjoki and 1.89 m^3s^{-1} for River Yläneenjoki (Table 4).

The River Yläneenjoki had higher mean Q than River Pyhäjoki in all four (2010-2013) years analyzed. Furthermore, the River Yläneenjoki had higher flow rates but smaller part of the river flow was estimated to be baseflow according to the baseflow analysis (Table 4). The higher quantitative amount of baseflow was related to the typically higher flow rates in the River Yläneenjoki subcatchment (HERTTA database).

The first pass of the baseflow filtering conducted following results (2010-2013): 0.36-0.64 m^3s^{-1} which was 69-73 % total of mean discharge for the River Pyhäjoki. River Yläneenjoki had the baseflow ranging from 0.79 to 1.05 m^3s^{-1} for the first pass, estimated baseflow represented 53-56 % of the total mean discharge during analyzed years 2010-2013 (Table 4).

The results between first and second pass in River Pyhäjoki varied from 0.28-0.64 m^3s^{-1}, which is 73-54 % of the total mean discharge between years 2010-2013 (Table 4), whereas, in River Yläneenjoki the baseflow proportion was 1.05-0.47 m^3s^{-1} (56-31 % from mean discharge) (Table 4). The smallest estimation of baseflow with third pass ranged between: 0.23-0.33 m^3s^{-1} (45-55 %) for River Pyhäjoki and for River Yläneenjoki third pass gave 0.29-0.54 m^3s^{-1} (19-25 %) (Table 4). The most interesting year, 2011, represents for River Pyhäjoki the average baseflow year in these studied years (Table 4). In River Yläneenjoki, year 2011, has the lowest baseflow share of the studied years 2010-2013 (Table 4).

The results from the baseflow program were as follows: In River Pyhäjoki, the proportion of the estimated baseflow from the discharge were between 73-45 % in analyzed years 2010-2013 (Table 4, Figures 16,18,20,22). In River Yläneenjoki the estimated baseflow between all three passes, varied from 56-23 % in years 2010-2013 (Table 4, Figure 17,19,21,23).

In years, 2010, 2011 and 2013 the main storm event is in spring time (April) in both river systems (Figures 1-6). In the year 2010 and 2011, both of the rivers from January to the beginning of April have low flow conditions having flow and baseflow less than 0.5 m^3s-

[1] as daily mean discharge. At that time the surface runoff is very close to the baseflow or equal to baseflow (Figures 16-19).

The spring season from April to the beginning of the mid-summer has the highest baseflow rate of the year in 2010 in both rivers, Pyhäjoki and Yläneenjoki (Figures 16 and 17). River Yläneenjoki has the maximum discharge reaching over 20 m^3s^{-1} in mid-April of year 2010 and River Pyhäjoki again has values over 4.5 m^3s^{-1} at that time (Figures 16 and 17). However, in the year 2011, River Pyhäjoki reaches the maximum discharge of 6 m^3s^{-1} and highest baseflow is over 2.5 m^3s^{-1} (Figures 18 and 19). River Yläneenjoki has the maximum discharge rate at the same time than River Pyhäjoki and the maximum discharge reached is 25 m^3s^{-1} and baseflow level is over 10 m^3s^{-1}.

In year 2012 there are several smaller discharge peaks in River Pyhäjoki and Yläneenjoki but the highest discharge rate of the year is related to higher precipitation in mid-October (Figures 20- 21)The baseflow in River Pyhäjoki is quite stable, staying between over 0 and 2 (m^3s^{-1}) during the year 2012 in all 3 passes (baseflow estimations) (Figure 20). Baseflow values in River Yläneenjoki seem more variable and the baseflow was between 0 and 8 (m^3s^{-1}) during the year 2012 in all passes (Figure 21).

The baseflow results of the year 2013 have a remarkable spring peak in the mid- April where the mean discharge and baseflow are considerably high compared to other discharge values of the year (Figures 22-23). The short storm event, which is seen as higher precipitation 18.4. 2013, reaches discharge rates over 9 m^3s^{-1} in River Pyhäjoki and in River Yläneenjoki the highest discharge rate is almost 40 m^3s^{-1} (Figures 22-23). However, the highest baseflow estimates of the year 2013 are only 2.5 m^3s^{-1} in River Pyhäjoki and 10 m^3s^{-1} in River Yläneenjoki (Figures 22-23).

During the studied years (2010-2013) and in both river systems, the highest baseflow estimation coincide during the largest storm events (highest mean flow rate) of the year. Depending of the year, the highest flow rates and baseflow rates were in spring time or during autumn.

The calculated baseflow values are between pass 1 and pass 2 for the baseflow (University of Calgary, Baseflow Program manual, Arnold and Allen 1999). The first pass has the largest estimated amount of baseflow, 2 nd and 3 rd passes are more reduced.

River Pyhäjoki had relatively larger proportion of groundwater in the river system compared to River Yläneenjoki, according to the results of automated baseflow separation. Recrusive digital filter has 3 passes that reduce the flow and the pass representing best the river baseflow condition depends on the characteristics of the subcatchment or the riparian aquifers/ area.

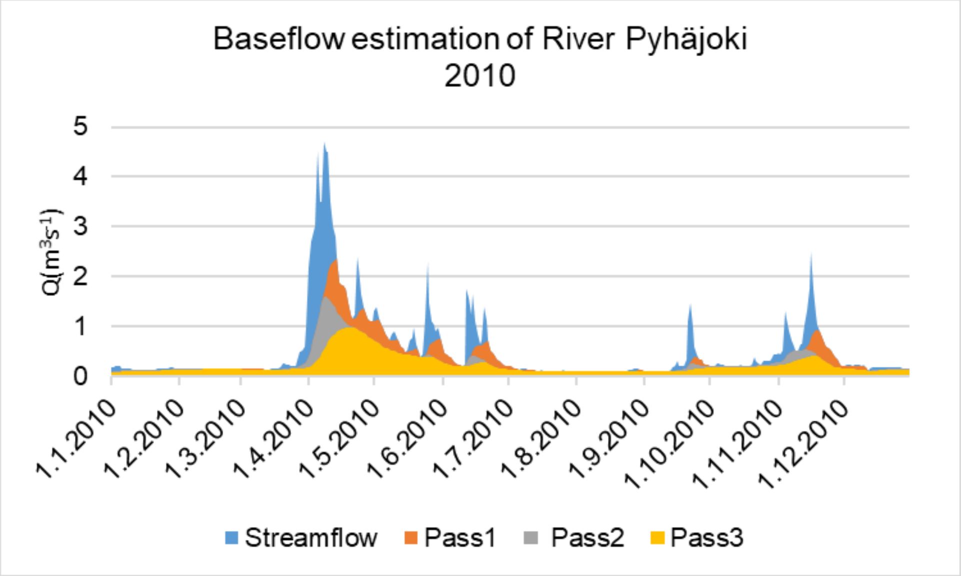

Figure 16. Daily mean discharge (m^3s^{-1}) and three passes representing different baseflow estimations of River Pyhäjoki in year 2010 made with automated digital filter program.

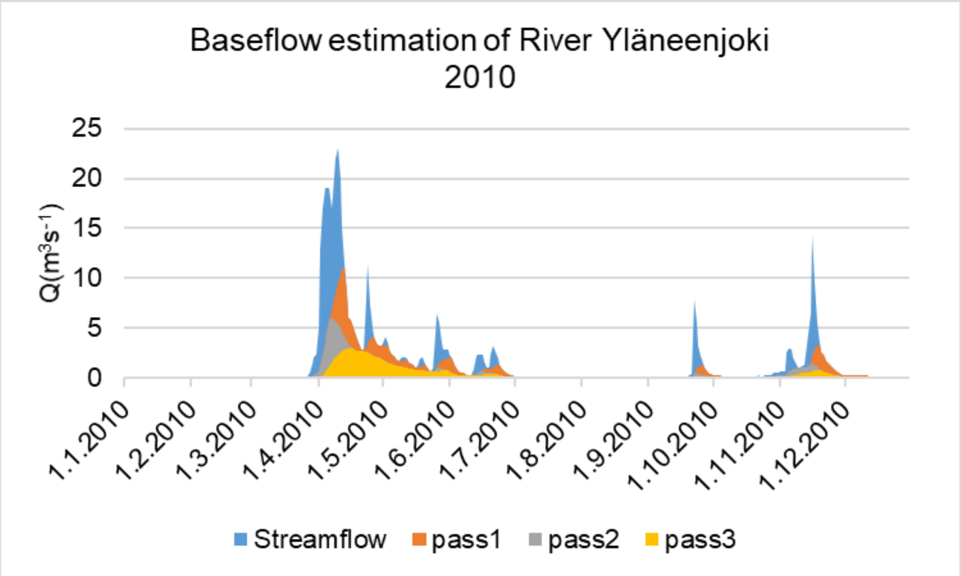

Figure 17. Daily mean discharge (m³s-¹) and three passes representing different baseflow estimations of River Yläneenjoki in year 2010 made with automated digital filter program.

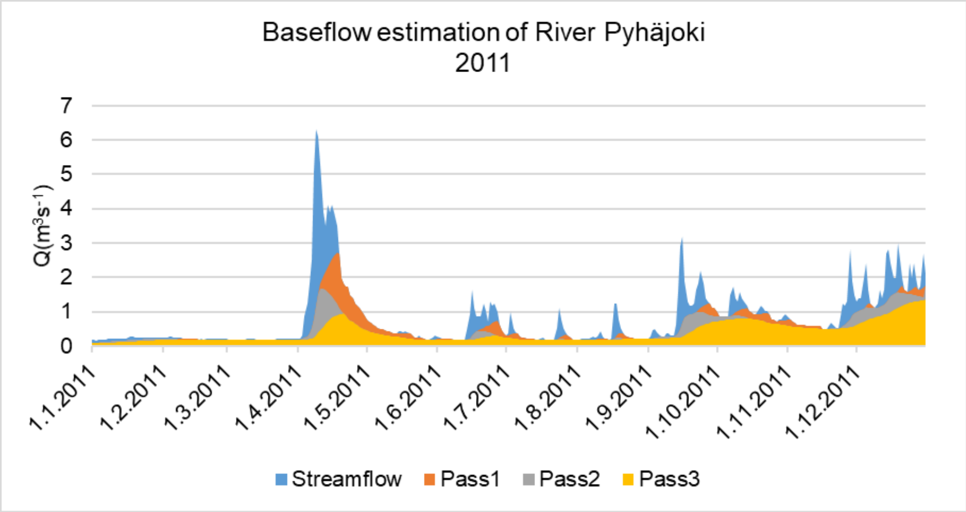

Figure 18. Daily mean discharge (m³s-¹) and three passes representing different baseflow estimations of River Pyhäjoki in year 2011 made with automated digital filter program.

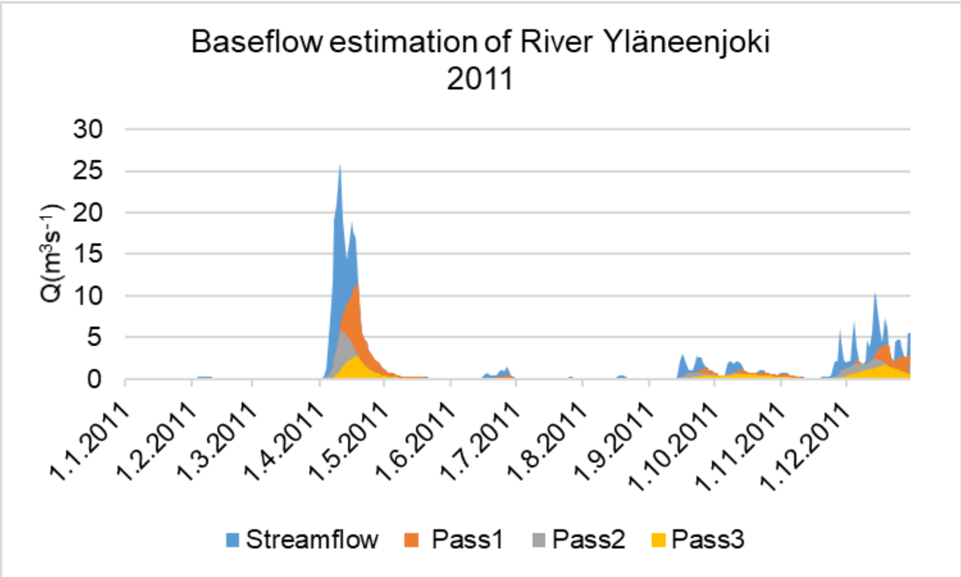

Figure 19. Daily mean discharge (m³s-¹) and three passes representing different baseflow estimations of River Yläneenjoki in year 2011 made with automated digital filtering program.

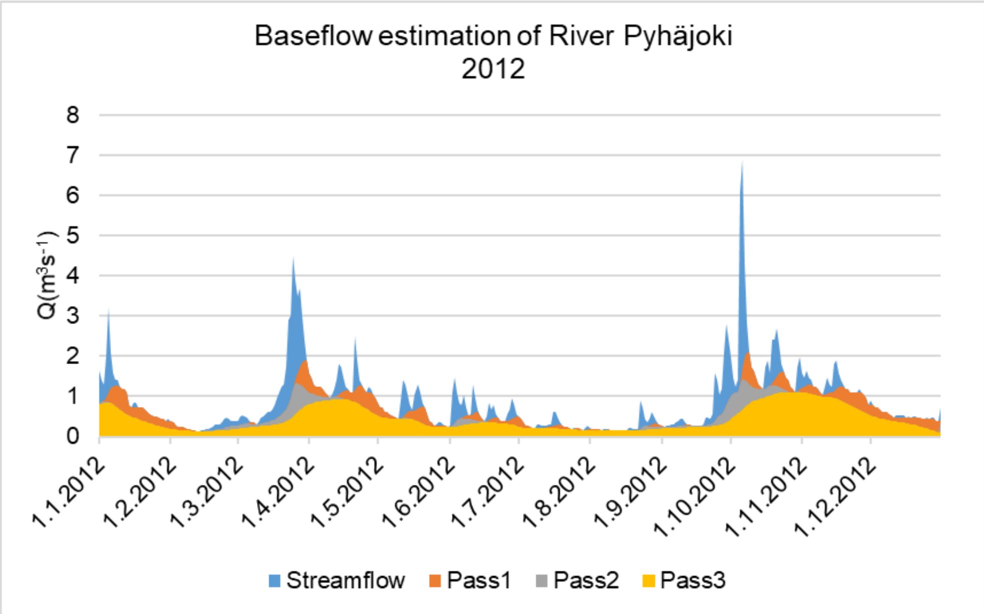

Figure 20. Daily mean discharge (m^3s^{-1}) and three passes representing different baseflow estimations of River Pyhäjoki in year 2012 made with automated digital filtering program.

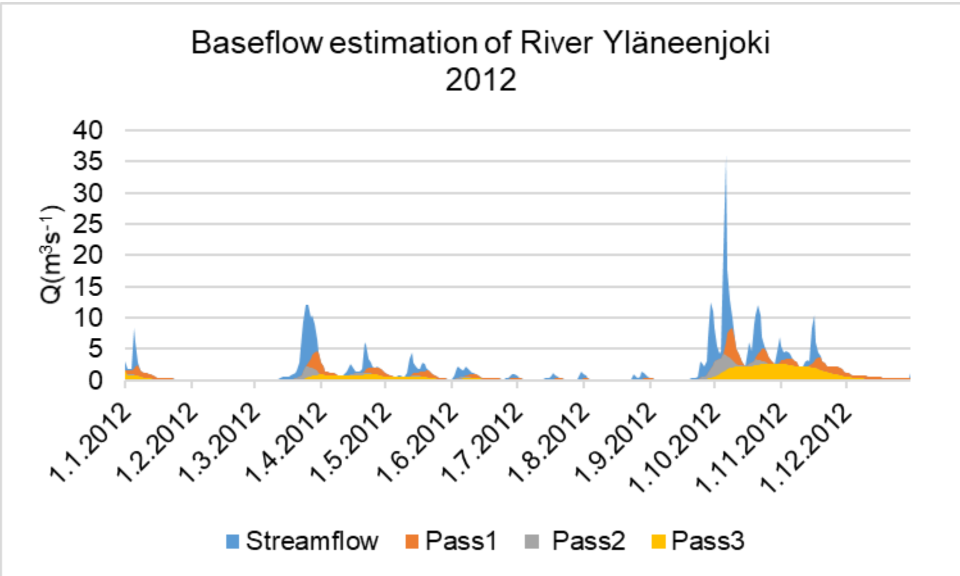

Figure 21. Daily mean discharge (m^3s^{-1}) and three passes representing different baseflow estimations of River Yläneenjoki in year 2012 made with automated digital filtering program.

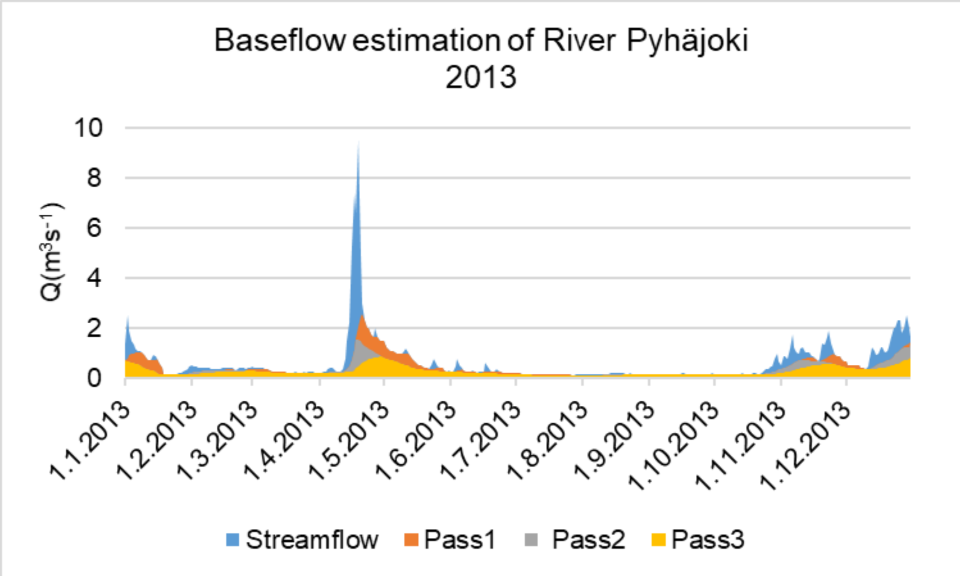

Figure 22. Daily mean discharge (m^3s^{-1}) and three passes representing different baseflow estimations of River Pyhäjoki in year 2013 made with automated digital filtering program.

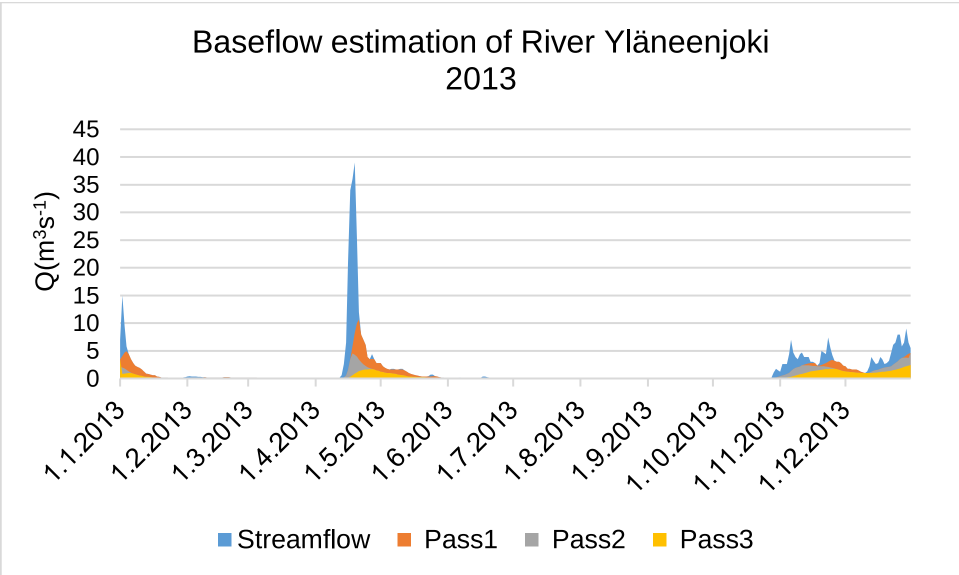

Figure 23. Daily mean discharge (m^3s^{-1}) and three passes representing different baseflow estimations of River Yläneenjoki in year 2013 made with automated digital filtering program.

5. DISCUSSION

5.1 GWD Categories in the two studied catchments

The GWD categories in River Pyhäjoki and Yläneenjoki subcatchments were as follows: 1) spring/springs, 2) diffuse discharge, 3) ditch/creek or any cold channel connecting to the river system, 4) wetland or wide seepage in the riparian area and 5) unknown anomalies that could not be defined because of the riparian vegetation. Total amount of GWD locations were approximately 200 in the two studied river catchments (Table 3, Figure 15). River Pyhäjoki has smaller river length and smaller catchment size and therefore had less GWD locations: 19. According to this TIR survey River Pyhäjoki catchment is characterized by diffuse anomalies. On the other hand, River Yläneenjoki having a larger catchment size, has almost 10 times more anomalies than River Pyhäjoki and discrete anomalies are more represented in the catchment.

Depending on the scale of the study, small springs can be taken into account in the discharge categories and they can be separately placed on the map. In this large scale study, smallest springs close together were counted as one in the GWD category (Figure 15). The large scale map mainly represents the locations where the springs occur along the river, some points might have partly same springs than previous location. The map illustrates the observed locations where the springs occur in these two studied rivers.

Rautio et al. (2015) observed, that larger amount of discharge categories is sometimes related to coarser glaciogenic deposits near riverbed. However, the coarser glaciogenic sediments do not seem to correlate to the amounts of GWD anomalies in the two studied rivers. River Yläneenjoki has way more anomalies (180) compared to River Pyhäjoki that has 19. River Pyhäjoki is near Virttaankangas esker complex and has more coarse deposits along the catchment. The sourcing spring brook of Myllylähde is excluded from the GWD place count and described as separate unit of GWD influence to the River Pyhäjoki (Figure 11). The GWD locations are counted from the main channel and its riparian area in River Pyhäjoki.

In River Yläneenjoki, the aquifers are rather small and have long distances between each other (Figure 5). River Yläneenjoki is not situated in the proximity of any large esker, only small till aquifers occur in the catchment (Figure 5). The sandy tills and coarse silts are usually connected to plural GWD anomalies close to each other in River Yläneenjoki, for example Kynnenoja (Figures 3 and 15) and in the proximity of small sandy till aquifer Laihia (Figure 5, HERTTA database 20.3.2020). Some small sand and gravel deposits further from the main channel could be connected to cold tributary discharging water to the main channel in nearby areas (Figure 15). Spring Myllylähde of Oripää is connected to the Orinpäänkangas esker and is one of the sources of River Yläneenjoki, which can possibly explain the different cold anomalies found in the headwaters Myllyoja area (Figures 5 and 15).

In Pyhäjoki subcatchment, especially in the proximity of Säkylä-Virttaankangas esker (Figure 15), there were some springs found from TIR images. GWD categories found in River Pyhäjoki are mostly associated with the sand and gravel and coarse grained tills (Figures 3 and 15). Also, higher GW contribution were found, characterized by diffuse discharge along the river or by shoreline in proximity of the two eskers: Porsaanharju and Säkylä-Virttaankangas (Figure 15).

Merged diffuse discharge class is used in this study. The category includes diffuse discharge by shoreline as described in Korkka-Niemi et al. (2012) and shown in Figure (13D). The diffuse discharge class along the main channel has also been used by Rautio et al. (2017). Adjacent TIR images that have diffuse discharge has been interpreted as one observation, as Kivimäki et al. (2013) describes the continuity of this GWD category.

There were no groundwater induced wetlands found with TIR data in River Pyhäjoki catchment. However, in River Yläneenjoki 18 wetland/wide seepage areas were interpreted from the TIR material and was able to connect the diffuse discharge into the river channel (Figure 15).

Rautio (2015) found a connection between springs and Quaternary deposits, coarse or medium grained: glaciofluvial silt, sand and gravel, glaciogenic till, but no direct connection between Quaternary deposits and diffuse anomalies or cold channels. However, in this study there seem to be a connection of glaciogenic till in one of the diffuse discharge areas in River Pyhäjoki and in diffuse discharge area in River Yläneenjoki, in the proximity of cold Kynnenoja channel (Figure 15, Figure 3).

River Yläneenjoki has few locations: where the most GWD areas occur according to TIR surveys. Same kind of clustering of different kind of GWD categories have been found in boreal catchments before. For example, the GWD category maps of Rautio et al. (2015) show that there are areas in River Vantaa catchment where several different adjacent GWD categories occur.

5.2 River temperature characteristics of River Pyhäjoki and Yläneenjoki

The focus in this study is on the relative temperature differences along the river catchments. T_{minr} of the two studied rivers varies along the catchments. The T_{minr} analysis (Figures 17,18 and 19) shows a pattern where the both studied rivers have headwaters with lower T_{minr}. River Pyhäjoki has a clearer warming trend from headwaters towards downstream (Figures 17 and 19). The relative river water temperature in the River Pyhäjoki decreased from the river mouth to the river upstream approximately 5°C. The temperature range was slightly larger in River Yläneenjoki and the temperature varied 6 °C along the river (Figure 18). Rive Yläneenjoki had relatively more discrete discharge locations and remarkable declinings varying from 3 to 6 °C of river water temperature (Figure 18).

The temperature varied in the River Pyhäjoki between 13 and 18 °C (Figures 17 and 19), however, notice the error of 0.7-0.8 °C in the image processing. Close to the mouth of the river Pyhäjoki, there are discrete temperature cooling locations and one remarkable decreasing of the radiant river water temperature due to a spring discharging in the River Pyhäjoki (Figure 17b). River Pyhäjoki has remarkably lower river temperature than River Yläneenjoki when the river water temperatures of the two studied rivers are compared according to T_{minr} results.

This cooling trend from the river mouths towards the headwaters has been detected in other TIR studies made in boreal catchments in Finland, where the river water temperature patterns have been observed (Rautio et al. 2015, Rautio et al. 2017, Lindgren 2018).

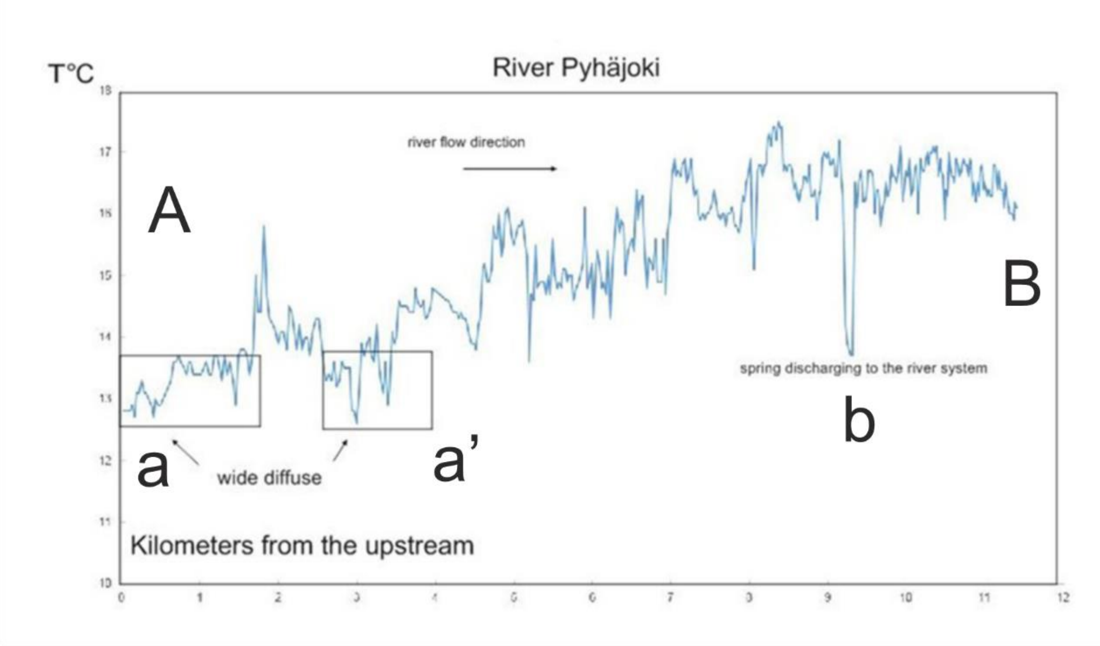

Figure. 17. Tminradiant graph made with the gps- data and Tminradiant method in River Pyhäjoki. There is a clear increasing trend, the minimum radiant temperature increases from the upstream towards Lake Pyhäjärvi, about 5 degrees celcius. Kilometers from upstream are approximately related to the stream length because the graph is from flightpath data. The analysis reaches to the beginning of the main channel of River Pyhäjoki.

In River Pyhäjoki, the warmest temperatures occur in the downstream and the temperature is approximately 19 °C or higher (Figure 18). The spring brook sourcing from the Myllylähde spring together with Kankaanranta spring lowers the minimum radiant temperature in the River Pyhäjoki in the upstream area (Figure 19). The two eskers: Porsaanharju that feeds Kankaanranta spring and Säkylä-Virttaankangas esker system feeding Myllylähde spring, are characterizing the very low river water temperature that occurs at headwaters of River Pyhäjoki, $T_{minr} \leq 14.5$ ° C. The Säkylä-Virttaankangas esker complex is in closer proximity of the River Pyhäjoki and follows the river several kilometers. The river temperature is gradually warming towards downstream after Kankaanranta Spring area (Figure 19).

T_{minr} of River Yläneenjoki varied between 14- 20 °C in River Yläneenjoki. With reflected temperature correction, adding 0.7-0.8 °C to the river water T_{minr}, the temperature of river water downstreams is very close to the lake water temperature which was approximately 20°C in the field day. The sourcing spring of Oripää that is connected to the main channel of River Yläneenjoki by Myllyoja shows a clear diminishing of the river water temperature (around 5 °C) compering to outflow of River Yläneenjoki (Figure 19). There is a cold channel connected to the river decreasing the River Yläneenjoki temperature about 5 °C which is clearly seen in the temperature profile (Figure 18). Most remarkable diffuse discharge areas of River Yläneenjoki are marked in the graph (Figure 18).

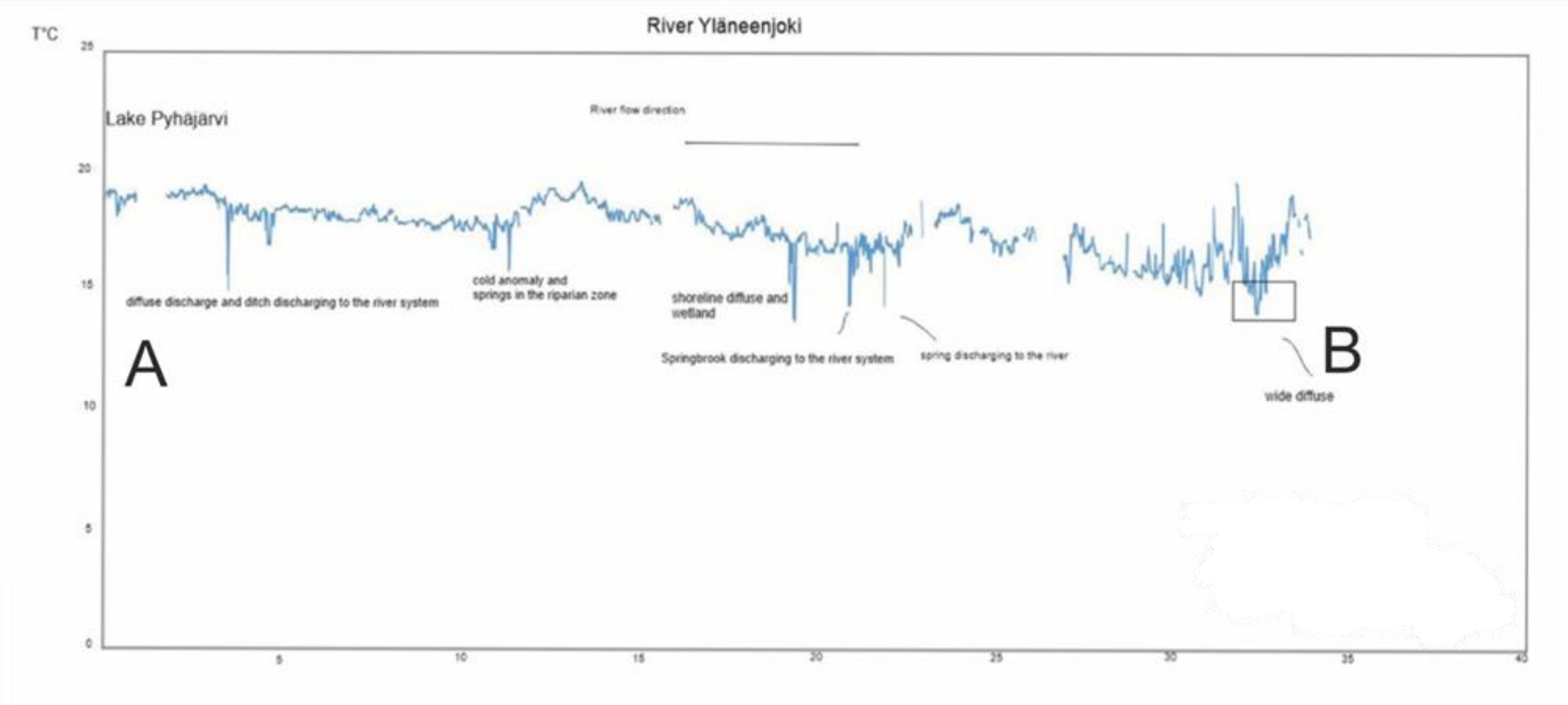

Figure 18. T_{minr} profile of River Yläneenjoki. Tminradiant graph made with the gps- data and Tminradiant method. There is an increasing trend in the minimum radiant temperature from the upstream towards Lake Pyhäjärvi, Kilometers from upstream are approximately related to the stream length because the graph is from flightpath data.

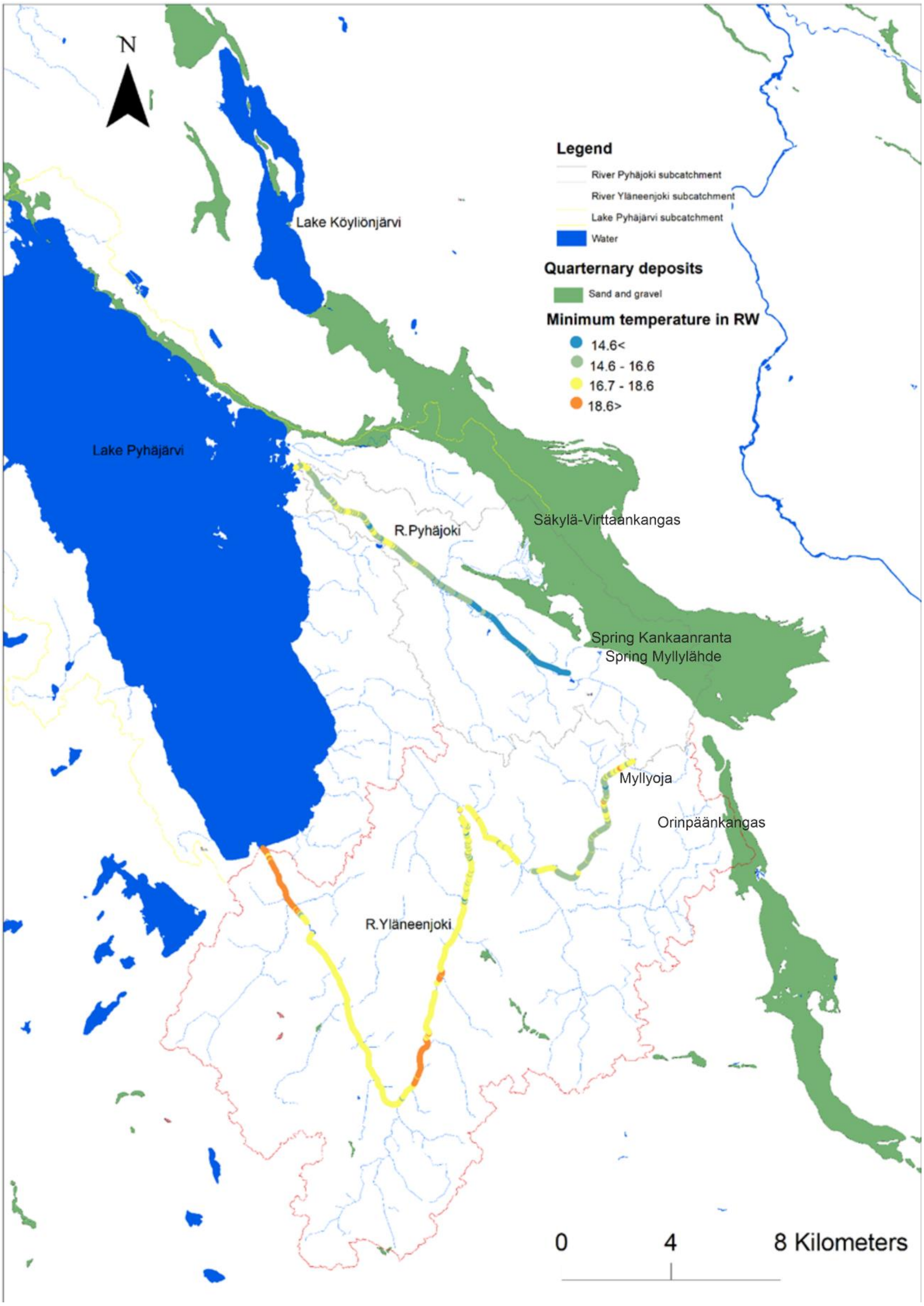

Figure 19. Tminradiant profiles of the two studied inflow rivers. Watershed-tool VALUE, Uoma10, Finnish Environment Institute © sand and gravel aggregate, geological survey of Finland ©

5.3 Connection between T_{minr} and GWD categories

The connection between lower T_{minr} and detected GWD categories in the studied river channels and riparian areas are somewhat clear in few circumstances:1) spring in the river, 2) diffuse discharge, 3) cold channels, also lower the T_{minr} of the main channel. Rautio et al. (2018) also noticed the connection between decreasing T_{minr} discrete and diffuse anomalies as well as cold tributaries. Usually, the cold channel connected to the main river channel, has a lower temperature than the main channel. In this study- in River Pyhäjoki, there is a cold channel connected to the main channel which has T_{minr} of 13 °C and the main channel has temperature close to 15 °C in that location. Rautio et al. (2015) noticed a 1-2 °C temperature difference related to cold tributaries in temperature profiles made from the main channels and Salonen et al. (2014) remarked a 2 °C lowering in the main channel due to cold tributaries.

5.4 Baseflow analysis and groundwater portion in the river catchments

The first pass was selected to be the most representable estimation of relative amount of baseflow in River Pyhäjoki and Yläneenjoki (Figures 20-27). The first pass was chosen based on PART-adjusted baseflow estimation made from the Rivers Pyhäjoki and Yläneenjoki by Wiebe (2012) and Wiebe et al. (2015). Recharge estimation methods, several baseflow estimations methods or recession analysis, have previously been used in in order to choose the most representing baseflow pass for the studied river (Arnold et al. 1995, Mau and Winter 1997, Rutledge 1993). Arnold and Allen (1999) noticed that when studying several catchments with digital filtering, most of the catchments baseflow estimations were between 1-2 passes in different kind of watersheds. If the hydrogeological conditions are not well known, generally the first pass is often used for representing the catchment (Arnold et al 1995). The results of baseflow analysis are also compared with other groundwater-surface water related studies made in the Lake Pyhäjärvi catchment (Karesvuori 2015, Rautio and Korkka-Niemi 2015).

The first pass computed by the baseflow program gave an estimation of 73- 69 % (Table 4, Figures 20, 22, 24 and 26) of baseflow contributed streamflow in 2010-2013 for River

Pyhäjoki. Baseflow indexes (BFI) are the relatives amounts of baseflow from total flow. The mean BFI for years 1971-2008 from Wiebe (2012) baseflow study made with PART-adjusted water balance study, were 78 % for River Pyhäjoki. However, the hydrograph separation study made by Karesvuori (2015) estimated that the river water of River Pyhäjoki has 66-68 % of old water, which is assumed to be almost entirely groundwater. These two previous studies are well in line with the baseflow filtering results made for River Pyhäjoki for years 2010-2013.

The baseflow analysis of this study gave results where the fraction of baseflow from streamflow was between 56-53 % in River Yläneenjoki when the first pass is chosen to be the best groundwater estimate (Table 4, Figures 21,23,25,27). The results are somewhat in line with the PART-adjusted baseflow results made by Wiebe (2012) who estimated the mean BFI to be 65 % for River Yläneenjoki. The PART-method used by Wiebe et al. (2015) gave results where the mean BFI was a little bit higher: 68 %. However, according to the DSi based GW share calculations in Rivers Pyhäjoki and Yläneenjoki made by Rautio and Korkka-Niemi (2015) gave results where Yläneenjoki had 54 % of estimated baseflow from streamflow which is well in line with the baseflow separation made in this study.

The relative amounts of baseflow from total discharge estimated with baseflow filtering gave similar results compared to other GWD related studies made for the two inflow rivers of the Lake Pyhäjärvi catchment (Wiebe et al. 2015. Wiebe 2012. Karesvuori 2015, Rautio and Korkka-Niemi 2015). The results conducted in this study were most similar with the studies of Rautio and Korkka-Niemi (2015) and Karesvuori (2015). The momentary studies, representing the same years were more in line with baseflow results of this study. The differences in GW estimations made between hydrographical separation and chemical studies versus PART-adjusted studies might be related to the longer time series used in PART- adjusted runoff model.

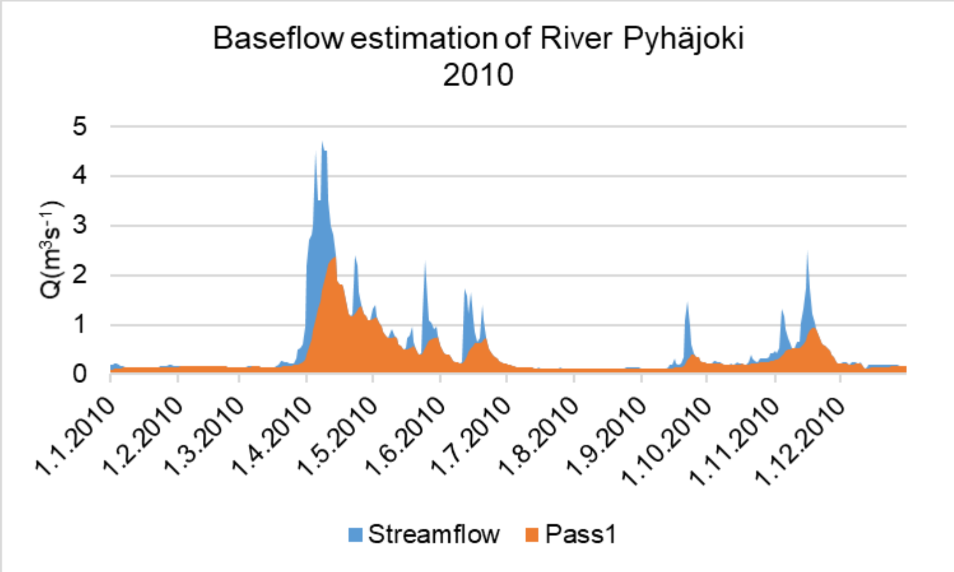

Figure 20. Figure 25. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Pyhäjoki (2010).

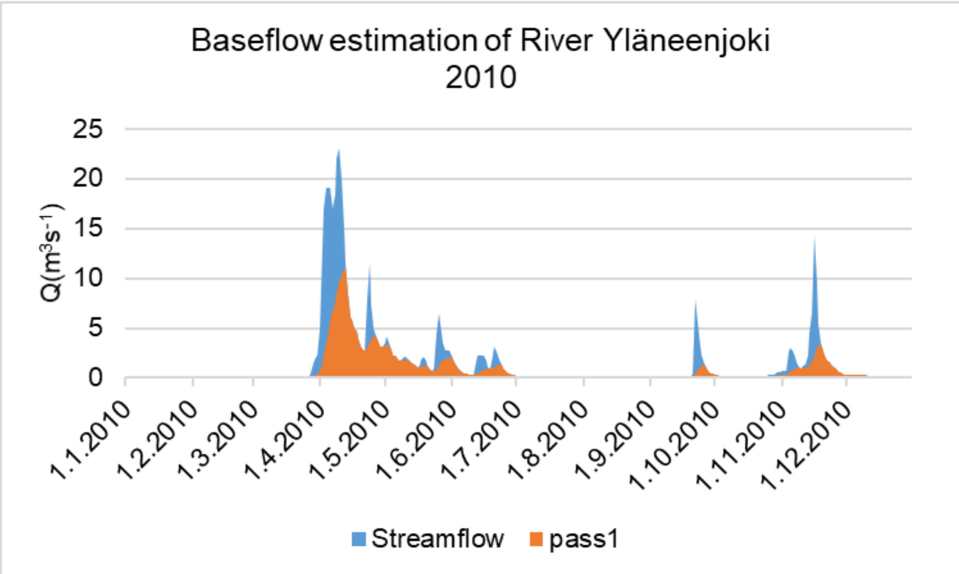

Figure 21. Figure 25. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Yläneenjoki (2010).

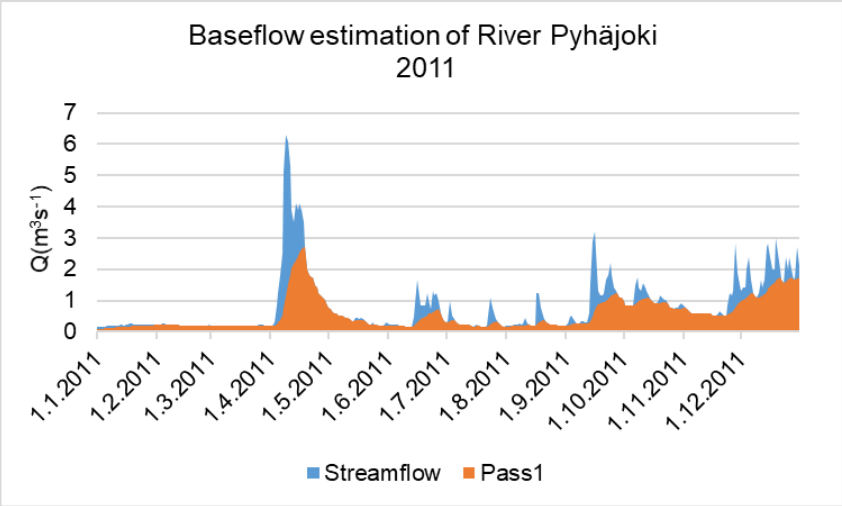

Figure 22. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Pyhäjoki (2011).

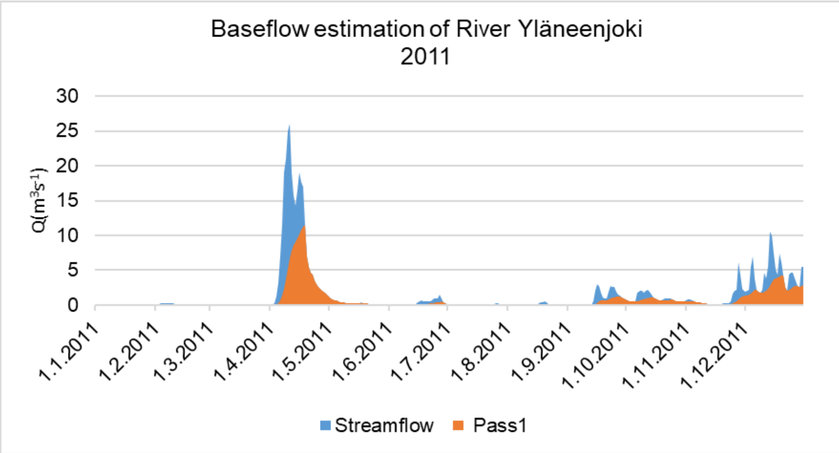

Figure 23. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Yläneenjoki (2011).

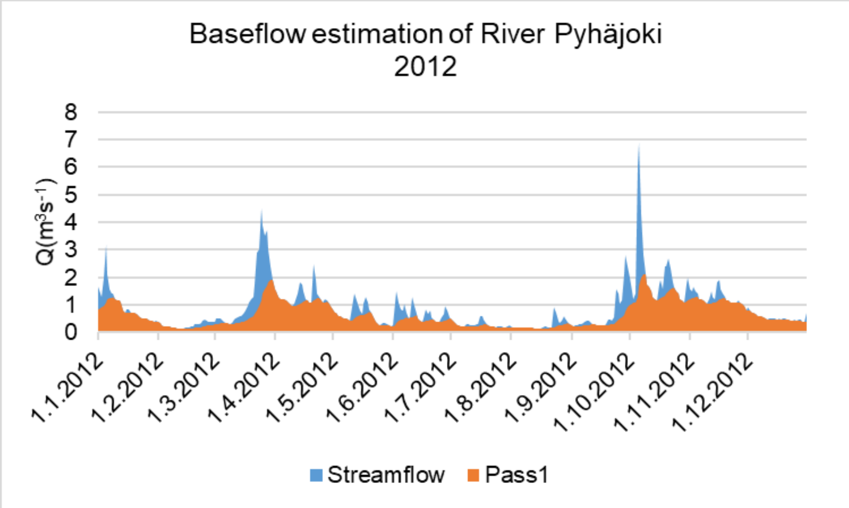

Figure 24. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Pyhäjoki (2012).

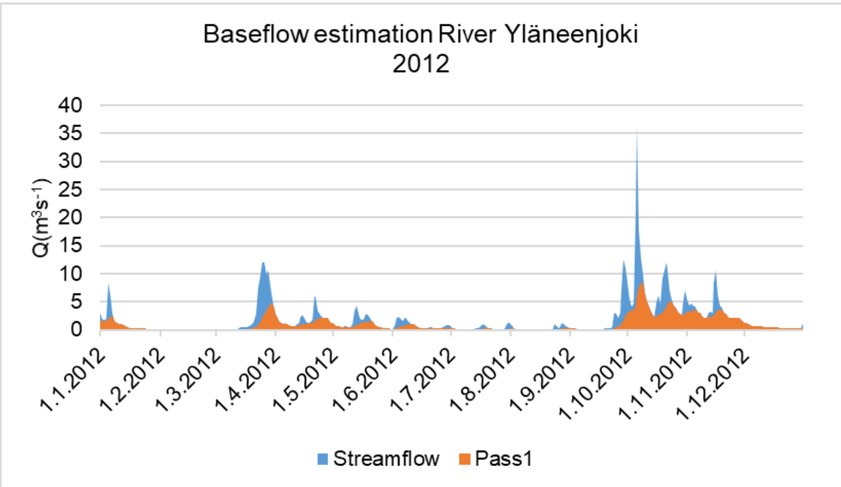

Figure 25. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Yläneenjoki (2012).

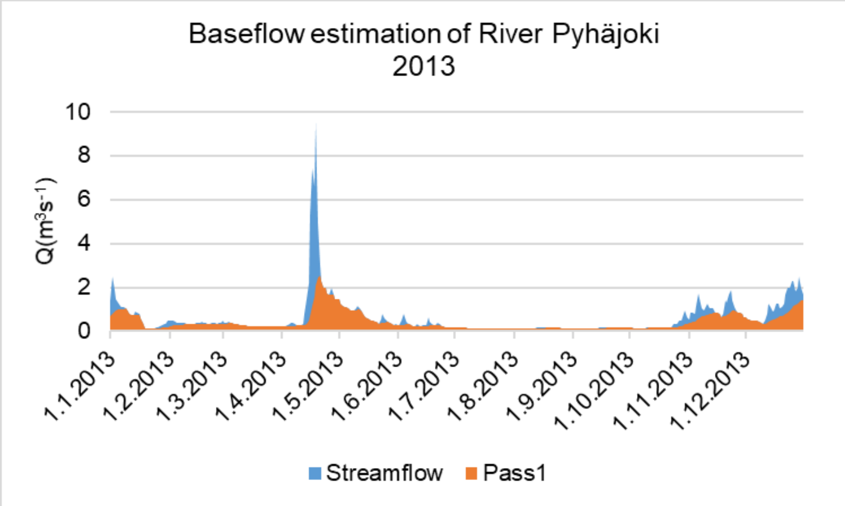

Figure 26. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Pyhäjoki (2013).

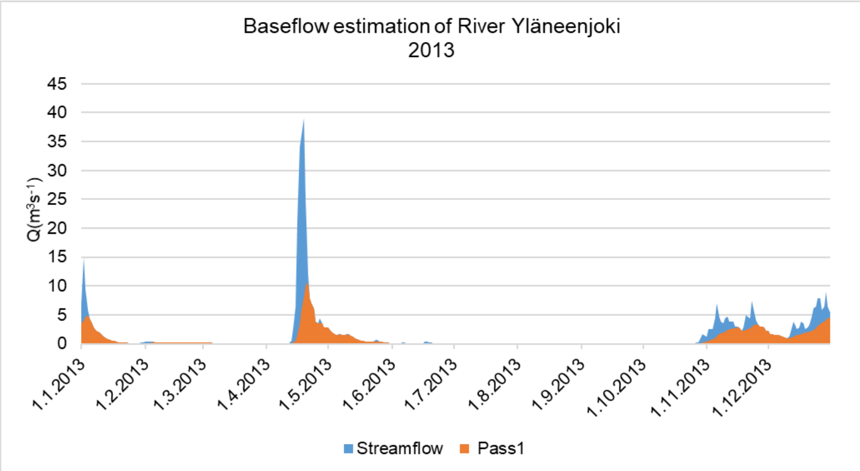

Figure 27. Daily mean discharge (m^3s^{-1}) and estimation of first baseflow pass made by digital filtering method for River Yläneenjoki (2013).

5.5 Applicability of TIR surveys and baseflow analysis in river baseflow estimation

The category map that shows small discrete GWD in the River Yläneenjoki (Figure 15) and higher radiant water temperature, which could indicate lower GW contribution of River Yläneenjoki (Figures 18 and 19). The previous studies made in the catchment area confirm the lower GWD effect to the River Yläneenjoki compared to River Pyhäjoki

(Rautio and Korkka-Niemi 2015, Karesvuori 2015, Wiebe 2012, Wiebe et al. 2015). However, Torgersen et al. (2001), pointed out that only the skin layer of the water (0.1mm) can be detected and stratification of the river water can not be seen in TIR studies. Therefore, with the help of baseflow analysis, the GWD share estimate is much more accurate (Arnold and Allen 1999).

Processing the TIR images revealed a great impact of groundwater discharge from spring Kankaanranta and Myllylähde with decreasing river temperature towards headwaters of River Pyhäjoki, approximately 5 °C (Figure 19). There were also large areas of diffuse discharge parallel to the two large feeding springs and Säkylä-Virttaankangas esker complex (Figure 15). Spatial continuity of GWD in River Pyhäjoki can be observed from T_{minr} and diffuse discharge anomalies (Figures 15 and 19).

TIR surveys often represent only the GW condition on one day, like in this study of July in year 2011. Making TIR surveys on consecutive years could reveal some temporary GWD categories, for example. Utilization of the longterm stream temperature data from monitoring stations could improve the applicability of the temperature information extracted from TIR-studies (Torgersen et al. 2001). Several TIR studies made with consecutive years have been made by Dugdale et al. (2003) and Rautio et al. (2015), for example. TIR surveys made in several years a row gives possibility to study the difference between temporal and more permanent GWD areas in river catchments (Dugdale et al. 2013). Monitoring the river and catchment conditions many years and seasons gives a better view of the real dynamics of the hydrogeology in the catchment.

This TIR study shows that- temperature differences and discharge anomalies within small distance and continuous GWD anomalies and river temperature patterns can be seen with this method. Small springs are able to be detected and large wetland areas and diffuse discharge patterns can be observed from TIR data too (Figure 15). Rautio (2015) stated that also a shape and a size of the groundwater discharge site can be detected from the TIR data. Large diffuse anomalies can be detected and classified as one category as described in Rautio et al. (2018). On the other hand, Torgersen et al. (2012) noticed that even small GWD anomalies could be detected with TIR.

Spatial heterogeneity, small springs and groundwater induced wetlands and wide seepage areas are able to be detected with TIR. Therefore, TIR studies are needed: to take into account the spatial and temporal river water temperature into water management (Poole and Berman 2001). The sizes of the anomalies and overall temperature profile of the river water, as well as existence of feeding springs and their discharge have to be taken into account when estimating the GWD in the rivers with TIR surveys.

The baseflow filtering produced results were the estimated baseflow share for River Pyhäjoki was 73- 69 % and for River Yläneenjoki 56-53 % (Table 4). These results are well in line with previous baseflow or GW share estimations made from Lake Pyhäjärvi catchment (Karesvuori 2015, Rautio and Korkka-Niemi 2015, Wiebe 2012, Wiebe et al. 2015). The baseflow analysis is reproducible even it has no physical basis and it is purely signal processing (Arnold et al. 1995). The method is not time consuming and it is rather objective, and the analysis can be made from chosen time series (Nathan and McMahon 1990). Previous baseflow studies, precipitation data and knowledge of riparian aquifers are needed to evaluate the result of baseflow filtering. Mau and Winter (1997) underlines the importance of hydrological assessment skills when using baseflow separation methods. It is important to keep in mind that hydrogeological environments are way too complex to be evaluated carefully with automated baseflow separation (Nathan and McMahon 1990). Therefore, the baseflow filtering results can be seen as indicative results of baseflow portion in Rivers Pyhäjoki and Yläneenjoki which TIR results support with spatial data.

5.6. Uncertainty and issues related to TIR data and baseflow analysis

In most cases the significantly low minimum radiant temperature was the verifying factor for the groundwater discharge anomaly which was otherwise unclear. Other helpful way to verify the discharge anomalies was using terrain plans and ortho video that has been filmed simultaneously with TIR surveys. Rautio et al. (2015), (2018) used the same tools to define the temperature anomalies.

This study indicated that the GWD categories might be impossible to categorize from TIR images without being familiar with the study site. As an example: some GWD locations are partly or totally covered by vegetation or image quality have suffered. That is why GWD anomaly category unknown was defined and used (Table 3). Other difficulty in the interpretation is water discharging from culverts/large plastic pipes that can have a lower temperature and look like springs. Therefore, even if the anomaly is clearly water the provenance of the cold water is not always 100 % surely from GW resources.

Discrete and diffuse cold water anomalies have complex sources because of the human impact on the two studied rivers. Especially underground drains are common to the Yläneenjoki catchment (Gonzales-Inca et al. 2015) and the fields are mostly in the proximity of the river channel (Figure 6). In addition to, a big part of the riparian areas of the Rivers Pyhäjoki and Yläneenjoki are arable land and not in natural condition (Gonzales- Inca et al. 2015). The end of the sub-drainage pipes in these arable lands reaching the river channels can cause false interpretations of cold spring anomalies (oral communication Kirsti Korkka-Niemi, November 2019).

In this TIR survey made in July 2011, the sun started to warm up the surface of the river water (oral communication, Anne Rautio, 2017). Warming of the river water during the filming day have been noticed in other studies, as well (Dugdale et al. 2013, Faux et al. 2001, Torgersen et al. 2001). Due to the warming, some potential GWD locations can be missed.

This study focused on the relative temperatures in river water from the direction of the headwaters towards outflow of the Rivers Pyhäjoki and Yläneenjoki. Spatial temperature map and longitudinal temperature profiles were made from the two studied rivers. According to Faux et al. (2001) longitudinal temperature profiles are typical outcomes of TIR surveys. In this study, the higher reflected temperature used caused inaccuracy of the temperatures, but the error was consistent (0.7-0.8 °C) and there were no available reference temperatures from the field trip of 2011. Only known temperature was the lake water temperature around 20 °C during the survey (HERTTA database). If there were reference temperatures measurements made same time with TIR flights, the accuracy of the T_{minr} analysis can be examined with correlating the radiant temperatures from the TIR analysis with the kinetic temperatures measured simultaneously with TIR surveys (Dugdale et al. 2013, Torgersen et al. 2001, Rautio et al. 2015).

In addition to human errors, difficulties in the temperature accuracies, are caused by many radiative factors influencing to the T_{minr} (Torgersen et al. 2001, Figure 8). Torgersen et al. (2001) reminds of the filming angle and its effect to emissivity value. Too large observation angle can effect to the emissivity value (Handcock et al. 2006). However, relative temperature differences reveal river temperature patterns along the catchment, and this is considered to be more notable than the exact values of river temperatures (Handcock et al. 2006, Rautio et al. 2015).

The possibility to separate the river channel from the river bank with certain accuracy is determined by river width and pixel size (Handcock et al. 2006). In this study, the T_{minr} was made with the help of polygon tool in ThermaCam Research Pro program with excluding the riparian area from the channel and having the lowest radiant temperature of each second. Following was noticed in the defining the river limits in TIR surveys: there are a lot of things to be aware of even inside the polygon limiting the channel. There can be power transmission lines, floating vegetation, docks and boats causing temperature anomalies. Rautio et al. (2015) also noticed that the roads and power transmission lines produce cold anomalies that have to be detected and not confused being the $T_{minr..}$

The baseflow filtering program is not able to function if there are data gaps in the flow rate data. This can be tricky if there is no data available during whole year or low flow season. The filtered baseflow values concerning the two studied rivers in this study have to be handled with care because baseflow filtering is based on signal processing (Arnold et al. 1995, Arnold and Allen 1999). It is suggested to use different kind of baseflow separation methods in order to have the most representable understanding of the baseflow (Mau and Winter 1997).

6. CONCLUSION

TIR analysis and filtering baseflow analysis give an overall view of the baseflow portion and groundwater discharge into the two studied Rivers: Pyhäjoki and Yläneenjoki. The baseflow portion seem to be larger in River Pyhäjoki (70 %) than in River Yläneenjoki (54 %) according to baseflow filtering estimations in years 2010-2013. TIR results confirm the baseflow separation results where T_{minr} is lower in Pyhäjoki and Pyhäjoki has larger GWD anomalies throughout the river. River Yläneenjoki has more anomalies and higher T_{minr} but it is characterized mainly by discrete GWD. Earlier studies made from Lake Pyhäjärvi catchment affirm that the baseflow portion of River Pyhäjoki is larger than in River Yläneenjoki, as well.

The temperature analysis shows the tendencies and main temperature patterns and gradual warming of the water along the rivers from headwaters towards the river outlets. Also, some significant anomalies can be seen in the minimum radiant temperature differences. Categorizing different kind of GWD anomalies show the heterogeneity of the river catchments. Locations of GWD anomalies can be studied from TIR images. Larger areas of diffuse discharge or wetlands/wide seepage can be detected and evaluated with TIR method, as well as small discrete anomalies.

The baseflow filtering method is quite the opposite: the exact quantities and relative propotion of baseflow can be estimated with recursive digital filter method. The TIR surveys revealed two clearly different temperature patterns of the two studied rivers: Pyhäjoki and Yläneenjoki. River Yläneenjoki show more spatial heterogeneity in the temperature variation compared to the River Pyhäjoki. The TIR study showed a clear trend (5° C) of river water temperature increasing from headwaters towards outflow in River Pyhäjoki. The diffuse discharge observed in the main channel of River Pyhäjoki supports also that the GW interaction is remarkable in the River Pyhäjoki. The TIR results showed a more variable temperature pattern of River Yläneenjoki where temperature increased towards outlet as well.

The two methods studied, TIR and baseflow filtering, supported each other by giving different kind of information about the baseflow condition in the two rivers. With baseflow separation it is possible to study the relative baseflow portion in longer time series easily and cost effectively if there is enough flow rate and precipitation data available from the catchment. TIR studies are more expensive and laborious thus giving momentary information about the GW conditions in the catchment. The understanding of GW-SW interaction is going to be crucial in the future, especially when the climate change sets the water management and nature protection under pressure. The combination of TIR surveys with baseflow filtering is an effective way to understand groundwater discharge into the river systems.

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